Textural Characteristics of Coarse Sediments in Selected Streams of the Niagara Peninsula, Ontario

A thesis submitted to
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by

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ABSTRACT

The streams flowing through the Niagara Escarpment are paved by coarse carbonate and sandstone sediments which have originated from the escarpment units and can be traced downstream from their source. Fifty-nine sediment samples were taken from five streams, over distances of 3,000 to 10,000 feet (915 to 3050 m), to determine downstream changes in sediment composition, textural characteristics and sorting. In addition, fluorometric velocity measurements were used in conjunction with measured discharge and flow records to estimate the frequency of sediment movement.

The frequency of sediments of a given lithology changes downstream in direct response to the outcrop position of the formations in the channels. Clasts derived from a single stratigraphic unit usually reach a maximum frequency within the first 1,000 feet (305 m) of transport. Sediments derived from formations at the top of waterfalls reach a modal frequency farther downstream than material originating at the base of waterfalls.

Downstream variations in sediment size over the lengths of the study reaches reflect the changes in channel morphology and lithologic composition of the sediment samples. Linear regression analyses indicate that there is a decrease in the axial lengths between the intial and final samples and that the long axis decreases in length more rapidly than the intermediate, while the short axis remains almost constant. Carbonate sediments from coarse-grained, fossiliferous units

are more variable in size than fine-grained dolostones and sandstones. The average sphericity for carbonates and sandstones increases from 0.65 to 0.67, while maximum projection sphericity remains nearly constant with an average value of 0.52. Pebble roundness increases more rapidly than either of the sphericity parameters and the sediments change from subrounded to rounded.

The Hjulstrom diagram indicates that the velocities required to initiate transport of sediments with an average intermediate diameter of 10 cm range from 200 cm/s to 300 cm/s (6.6 ft./sec. to 9.8 ft./sec.). From the modal velocity-discharge relations, the flows corresponding to these velocities are greater than 3,500 cfs (99 m^3s). These discharges occur less than 0.01 per cent (0.4 days) of the time and correspond to a discharge occurring during the spring flood.

ACKNOWLEDGEMENTS

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INTRODUCTION

Problem Statement

Sedimentological studies of coarse sediments in the fluvial environment have primarily focused on sand and gravel size particles, while few investigations are available on the characteristics of coarser material. The streams flowing through the Niagara Escarpment cross eleven recognizable lithological units which produce a large volume of coarse carbonate and sandstone fragments.* Because the sediments have a known origin, they can be traced downstream from their source. As a result of these conditions, the boulder paved channels in the escarpment provide an excellent opportunity to study the characteristics and movement of coarse sediments in a high energy environment. The purpose of this investigation is to examine the variations in the frequency of each sediment lithology downstream from its source and determine the changes in axial lengths, sphericity and roundess of pebbles greater than 10 cm in diameter sampled from five streams flowing through the escarpment. In addition, fluorometric measurements and gauging station flow data will be used to examine the frequency of sediment movement.

Study Area

The streams chosen for this study have their headwaters above the escarpment and flow northward into Lake Ontario

*The terms pebbles, fragments, clasts, etc. are used interchangeably throughout and do not necessarily refer to the Wentworth Grade scale.

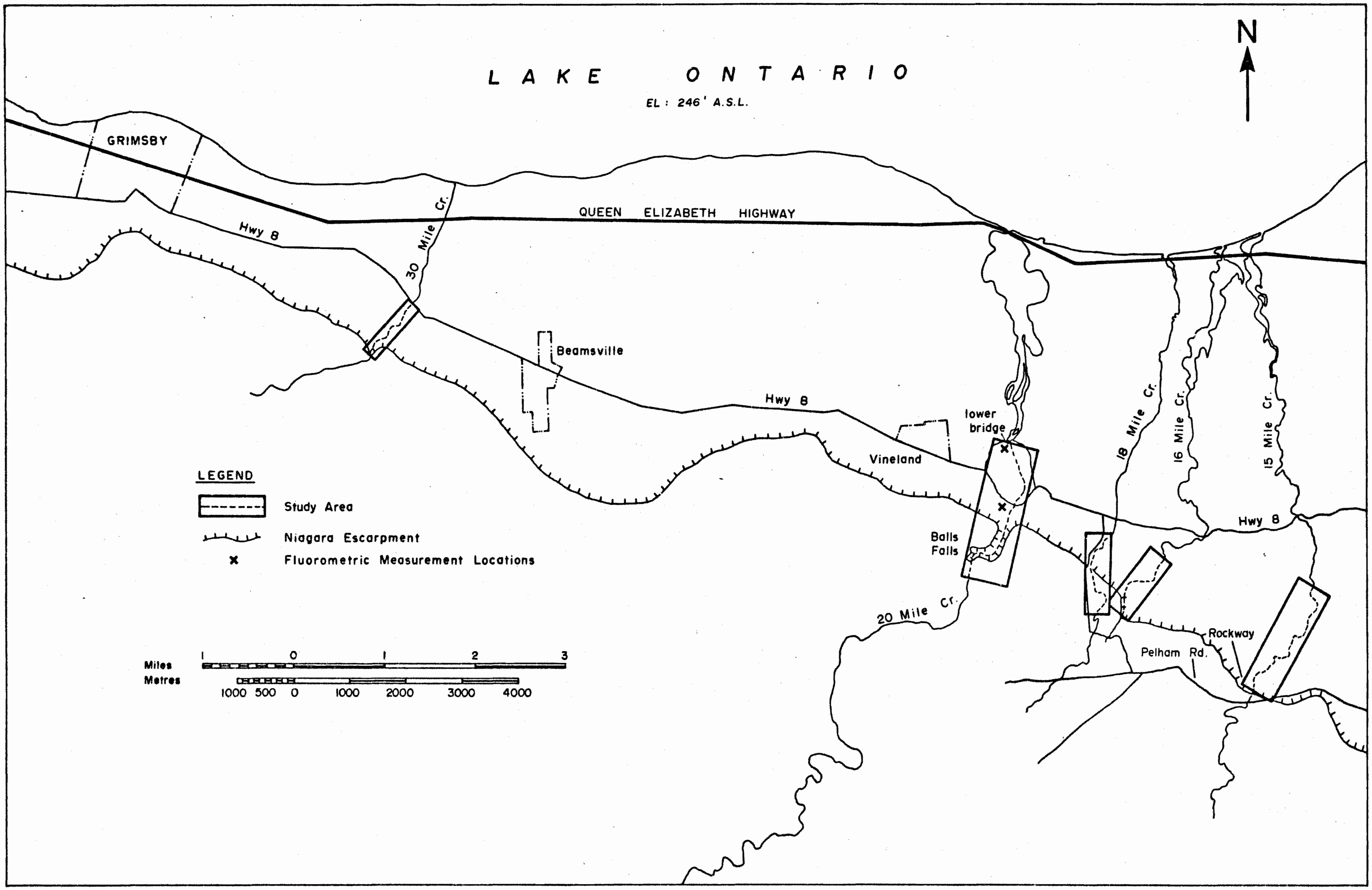

Fig. 1. Study area.

(fig. 1). They are located between St. Catharines and Grimsby and include: 15 Mile Creek, 16 Mile Creek, 18 Mile Creek, 20 Mile Creek, and 30 Mile Creek. These names indicate their mileages from the mouth of the Niagara River. Twenty Mile Creek is the largest with a drainage area of 113 square miles (294 km^2). The basin areas of the remaining streams range from 4 square miles (10.4 km^2) for 30 Mile Creek to 26 square miles (67.6 km^2) for 15 Mile Creek.

The reaches examined extend from the brow to the base of the escarpment (figs. 2 to 6). Through these sections, the channels contain a large volume of coarse carbonate and sandstone clasts, derived from the escarpment. The streams are easily accessible and the channels are dry in the summer which facilitates sediment sampling and channel measurements. Above and below the study reaches, the channels contain very few coarse fragments.

Previous Work

In a study of the Lower Colorado River, between central Texas and the Gulf of Mexico, Sneed and Folk (1958) examined the textural characteristics of quartz, chert and limestone pebbles ranging from 32 to 64 mm in diameter over a distance of 270 miles (432 km). They concluded that limestone clasts reach a limiting roundness value of 0.65 relatively quickly, whereas quartz rounds at a slower rate and chert only increases slightly. They also determined that sphericity was primarily a function of pebble lithology and was also dependent on sediment size and transport distance, but only

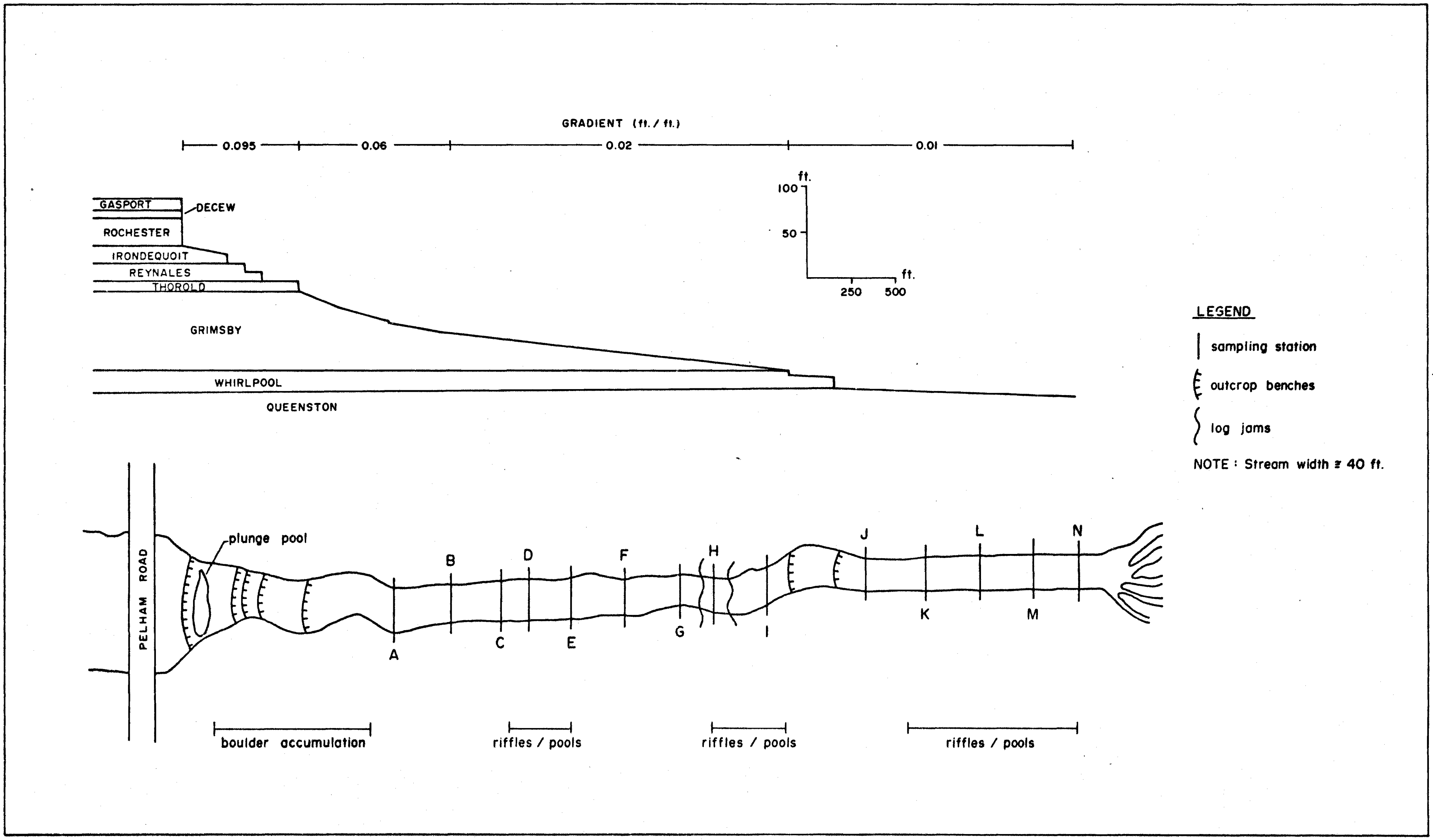

Fig. 2. 15 Mile Creek - Plan view and longitudinal profile. Same symbols used on figures 2 to 6. (1,000 ft. = 305 m).

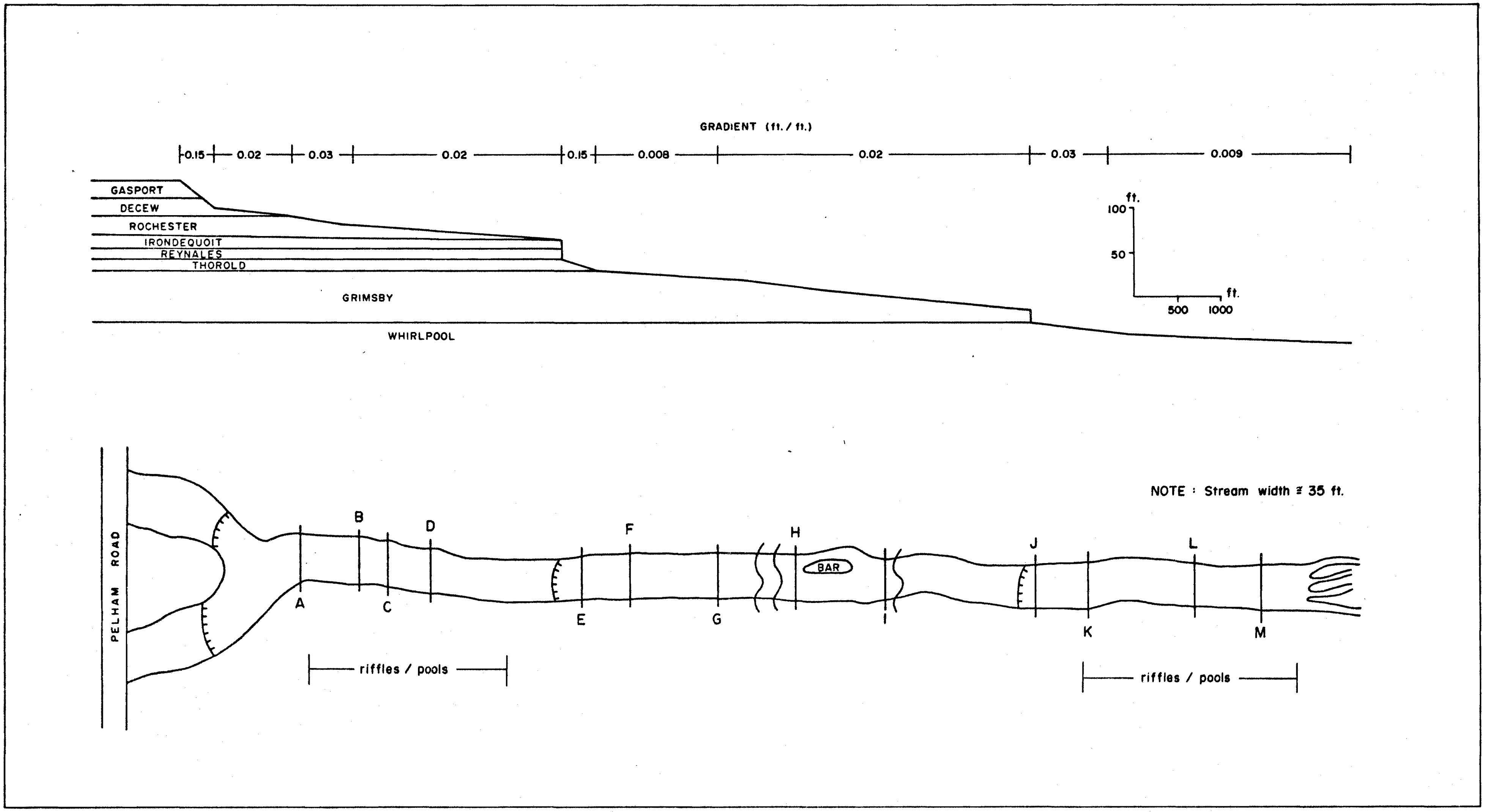

Fig. 3. 16 Mile Creek - Plan view and longitudinal profile.

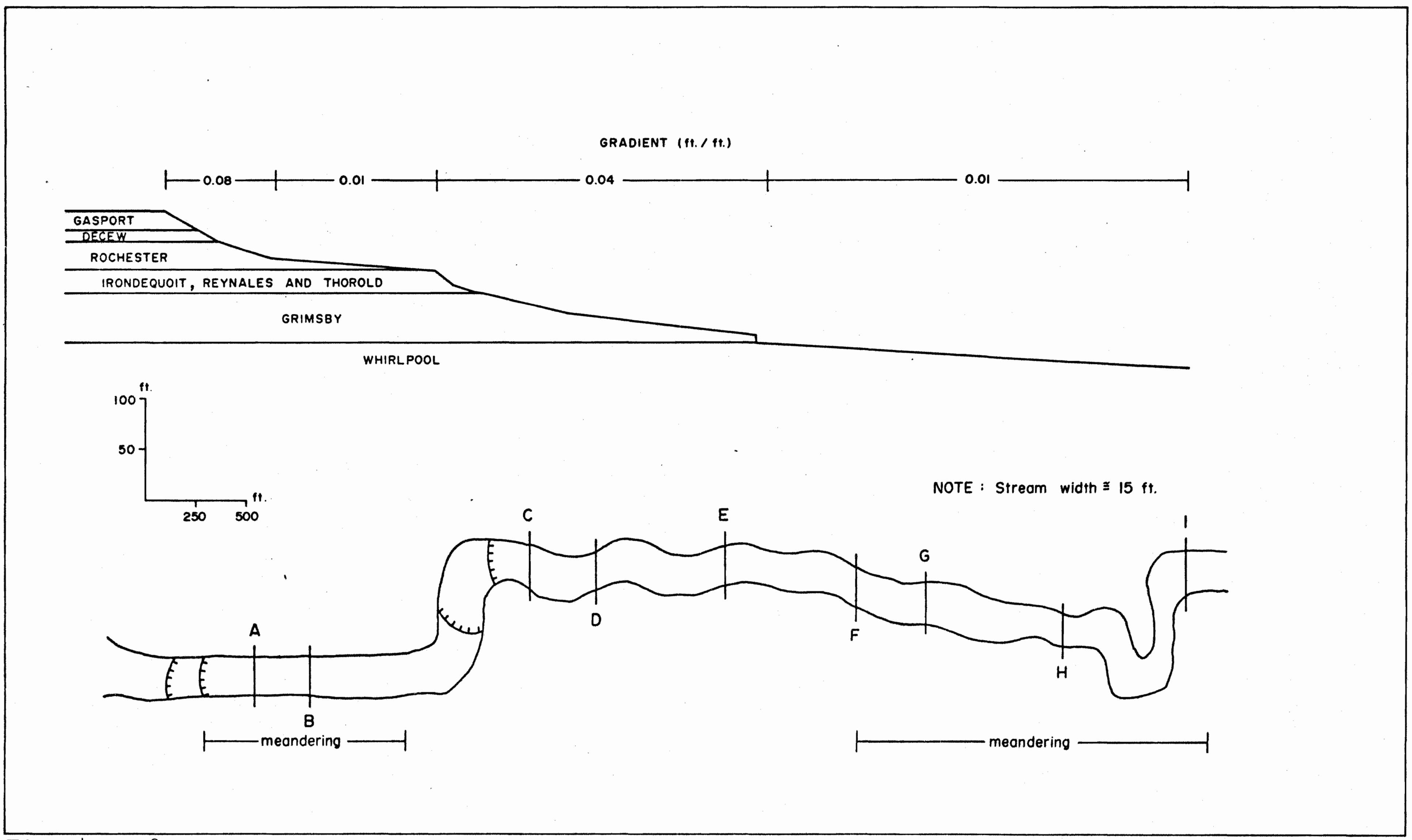

Fig. 4. 18 Mile Creek - Plan view and longitudinal profile.

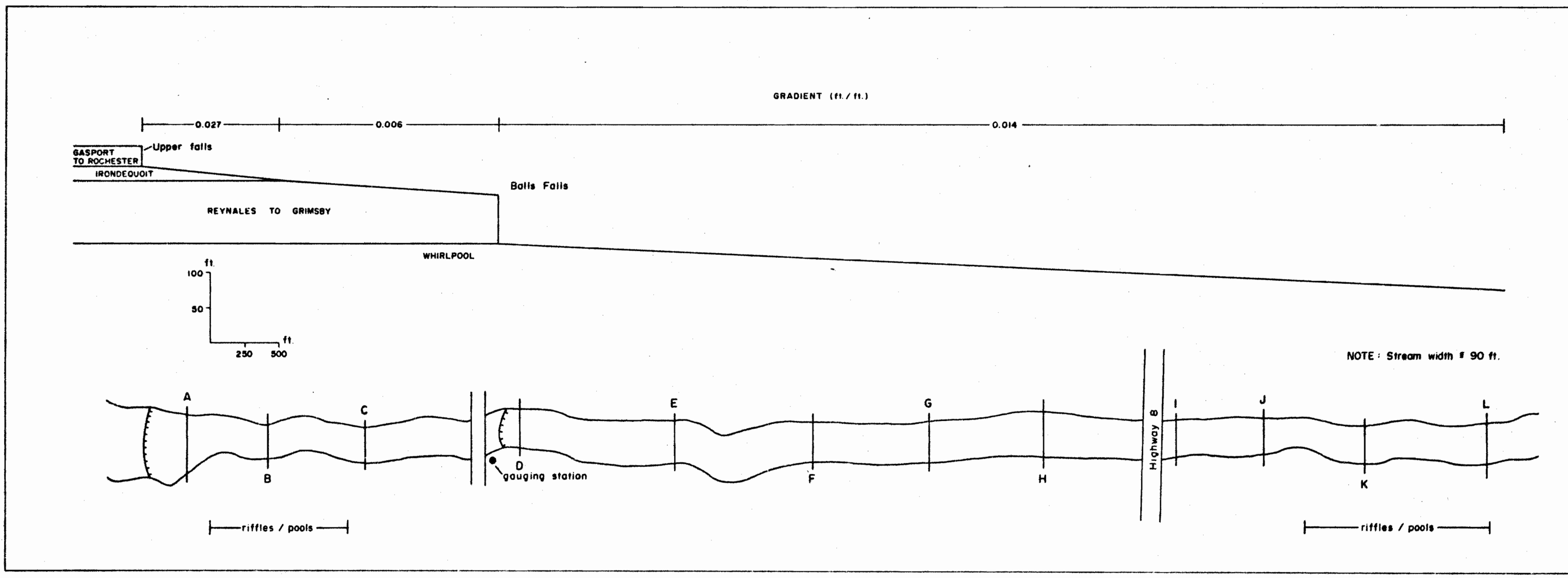

Fig. 5. 20 Mile Creek - Plan view and longitudinal profile.

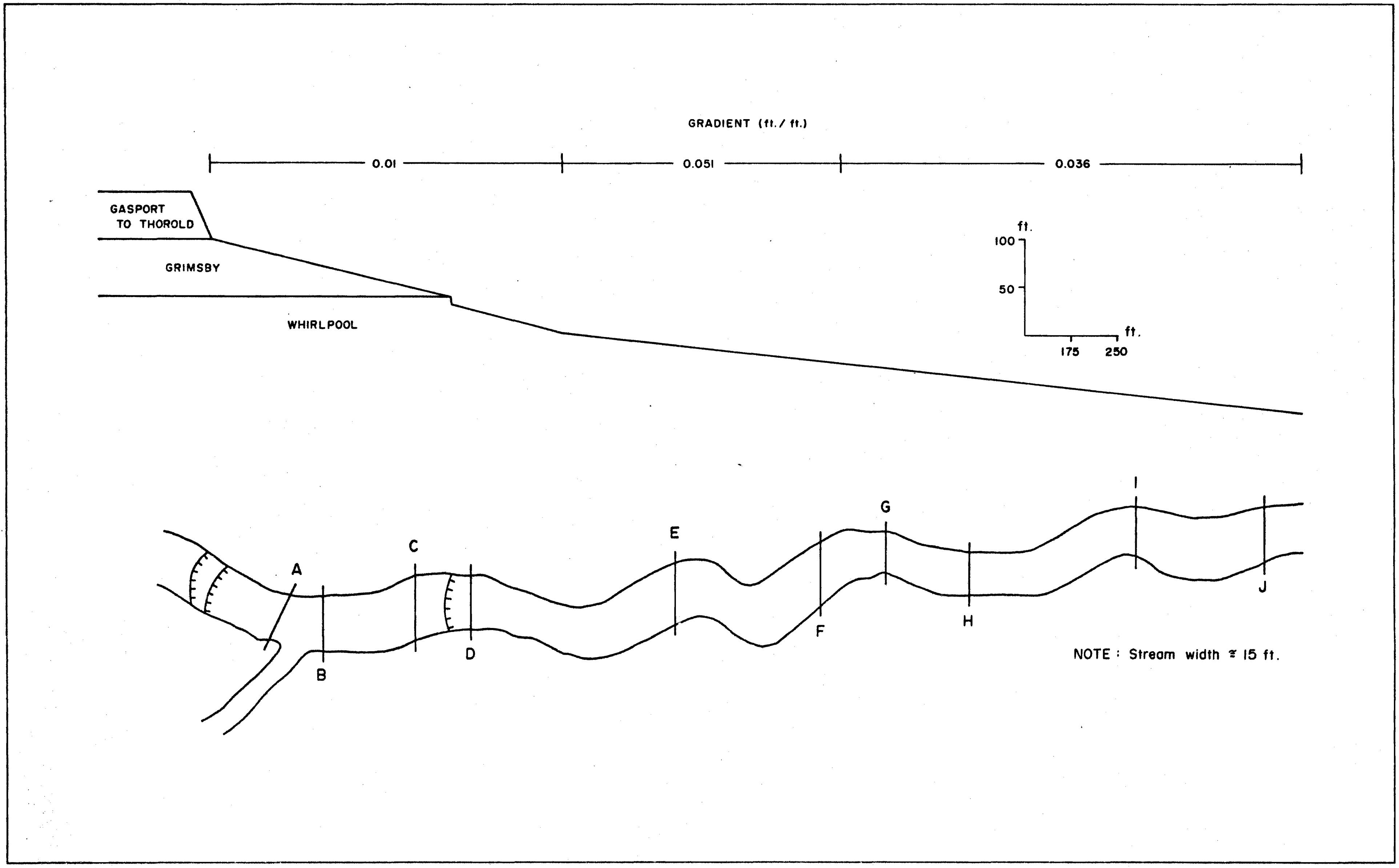

Fig. 6. 30 Mile Creek - Plan view and longitudinal profile.

slightly affected by sorting. Sneed and Folk (1958) also introduced a behavioristic sphericity measurement, called the "maximum projection sphericity" and a ternary diagram, based on axial ratios, was proposed for analysing sediment form. They concluded that particle size had the greatest effect on sphericity and form, in that large pebbles had low sphericity values and rodlike forms, whereas smaller fragments were discoidal in shape with higher sphericity values.

Krumbein (1940) studied coarse gravels deposited by a single flood event (March, 1938) in San Gabriel Canyon, California. He found that the sediments displayed nonsystematic downvalley changes in size, sorting, shape and lithology, whereas roundness and fabric showed systematic variations. He also proposed a detailed theory of pebble rounding based on the assumption that the rate of rounding is proportional to the initial and final roundness values of sediments in a given environment. In another study of flood deposits, resulting from the failure of a diorite-rockfill dam on the Rubicon River, California, Scott and Gravlee (1968) determined that rapid changes in roundness resulted from the extreme coarseness of the diorite fill. They also showed that grain size decreased rapidly downstream due to progressive sediment sorting. Helley (1969) studied the initiation of particle motion in Blue Creek, California and found that for gravel and coarser material, shape differences were more important in controlling movement than variations in specific gravity and particle orientation. Bradley, Fahnestock and Rowekamp (1972) examined the downstream changes in textural characteristics of coarse sediments carried by flood flows on the Knik River, Alaska. They concluded that changes in size and shape were mainly caused by sorting and that platy pebbles are the most transportable, elongated particles are intermediate, and compact (equidimensional) clasts are the least transported. Knighton (1976) studied sediments over the length of a river section in a small Rocky Mountain basin and determined that grain size varied significantly with lithology. Laronne and Carson (1976) suggested that sediment sorting and packing affect the transport rate of coarse sediments. They concluded that pebble transport distances increase with particle size for poorly sorted bed material due to tighter sediment packing.

Several studies have focused on the relation between sediment transport and channel hydrology. Birkeland (1968) examined the Truckee River glacial outwash sediments of the Tahoe Glaciation in California and Nevada and found that boulders and gravel bar deposits indicated greater discharges and velocities than those of the present river. He determined, using the Manning equation, that a mean flood velocity of nearly 30 feet per second (914 cm/s) must have occurred in order to transport these sediments. Wilcock (1971) studied a small upland catchment in the Pennines of England and found that different combinations of exponents in the hydraulic geometry equations were related to varying rates of increasing and decreasing stream competence. With increasing discharge and constant mean depth, there is an increase in the velocity/width ratio resulting in an increase of stream competence. Baker and Ritter (1975), showed that the DuBoys shear stress equation is a representative estimate of stress competence and concluded that braided or single streams with wide and shallow channels transport material more effectively than deep, narrow channels.

Bedrock Geology

The Niagara Escarpment extends west from Queenston, Ontario to Hamilton and north through the Bruce Peninsula to Manitoulin Island. This cuesta may be traced from the Appalachian Basin into the Michigan Basin, over the Algonquin Arch that bounds the Michigan Basin. (Liberty, pers. comm., 1977). There are approximately 2,000 feet (610 m) of Cambrian and Ordovician sediments between the upper surface of the crystalline Precambrian basement and the base of the escarpment (Winder and Sanford, 1972). The rocks of the escarpment range in age from Upper Ordovician to Middle Silurian. The type section is located on the Niagara River, about two miles (3.2 km) downstream of Niagara Falls (fig. 7). Although the escarpment formations appear to be flat-lying, the regional dip of the strata ranges from 20 to 22 feet per mile (3.8 to 4.2 m/km) to the southwest (Winder and Sanford, 1972). An extensive description and interpretation of the Silurian stratigraphy and paleontology of the Niagara Escarpment has been published by Bolton, (1957)

		Niagara Peninsula (Niagara Falls-Hamilton)			
				Formation	Member
Silurian	Niagaran Series (Middle Silurian)	Albermarle Group		Guelph	
				Lockport	Eramosa
					Goat Island
					Gasport
		Clinton Group	Upper	DeCew	
				Rochester	
				Irondequoit	
			Middle		
			Lower	Reynales	
				Neahga	
				Thorold	
	Alexandrian Series Lower Silurian	Cataract Group		Grimsby	
				Power Glen	
				Whirlpool	
Ordovician		Nottawasaga Group		Queenston	
				Georgian Bay	

Fig. 7. Classification of stratigraphy of the Niagara Peninsula (after Bolton, 1957).

and therefore only a brief summary will be presented.

The Queenston Formation is 450 to 500 feet (137 to 152 m) thick, but only a small portion of its upper part is exposed in the study area (Middleton, 1972). This formation consists of brick red, thin to medium bedded shale, often containing green mottling (Hewitt, 1971). Occurrences of thin beds of grey-green and reddish argillaceous limestone are also common. It is extremely fissile, blocky and easily weathered, which leads to the red, clay soils found in the Niagara Peninsula.

The Cataract Group (Alexandrian Series) consists, in ascending order, of the Whirlpool, Power Glen and Grimsby Formations. The Whirlpool Formation is a white to light grey, massive crossbedded sandstone and represents the lowermost Silurian formation of the Niagara Escarpment (Bolton, 1957). It consistently rests on the Upper Ordovician Queenston shale. Overlying the Whirlpool sandstone is the Power Glen Formation, consisting of dark grey to greenish-grey shales with grey to white, calcareous sandstone beds common throughout. The Grimsby Formation, which overlies the Power Glen shales, is composed of red, green mottled, irregularly bedded sandstone, with red shale interbeds passing downward into red, green mottled shales, with sandstone interbeds (Bolton, 1957).

The Clinton Group represents the lower part of the Middle Silurian (Niagaran Series) and includes, in ascending order, the following formations: Thorold, Neagha, Reynales, Irondequoit, Rochester, and DeCew. The Thorold Formation is comprised of white to light green sandstones and has a sharp lower contact with the Grimsby Formation (Bolton, 1957). The Neagha Formation consists of 7.0 feet (2.1 m) of green shale with a limestone interbed at Niagara Falls. However, west of DeCew Falls, the Neagha Formation rapidly pinches out and is not present at Grimsby (Bolton, 1957). Its upper contact with the overlying Reynales Formation is distinct. The Reynales Formation consists of light grey to blue, thin bedded, fine crystalline dolostone with shaly partings and the lower 2.5 feet (0.8 m) is somewhat limey and fossiliferous (Bolton, 1957). The Irondequoit Formation, above the Reynales, is a grey to reddish-brown, massive, dense to crystalline dolomitic limestone, with a sharp upper contact (Bolton, 1975). Above this contact is the Rochester Formation, which is a thick unit of dark grey, calcareous shale, containing many grey limestone interbeds in the lower half (Bolton, 1957). The highest unit of the Clinton Group is the DeCew Formation which overlies and has a gradational contact with the Rochester shale. The DeCew dolostone is grey, dense to very finely crystalline, thin to thick bedded and is easily identified by its conchoidal fracture (Bolton, 1957).

The Lockport Formation forms the caprock of the Niagara Escarpment and represents the youngest rock type in the study area. It is divided into three members which, in ascending order, include the Gasport Member, Goat Island

Member, and Eramosa Member. The Gasport Member is a bluish-grey, crystalline, crinoidal, massive to poorly bedded, buff-weathered, very porous dolomitic limestone (Bolton, 1957). The Goat Island Member is a light buff to light brownish-grey aphanitic to fine crystalline, massive to thick bedded dolostone, with occurrences of bluish-grey and white chert beds, known as the "Ancaster chert beds" (Bolton, 1957). The uppermost member of the Lockport Formation is the Eramosa Member. It is a dark brown to medium brownish-grey, aphanitic to sugary, medium to thin bedded, dark grey streaked dolostone, containing bituminous and shaly partings.

Quaternary Geology

All of the glacial sediments in the study area were deposited during the late Wisconsin. South of the Niagara Escarpment the bedrock is covered by a thin veneer of Wentworth and Halton Tills which thicken towards Lake Erie. Overlying these tills are the glaciolacustrine sediments of the Haldimand Clay Plain (Feenstra, 1972). The base of the escarpment is mantled by the Wentworth and Halton Tills which occur as morainic features. To the north, the lowland area between the escarpment and Lake Ontario is occupied by the Iroquois Lake Plain.

In the Niagara Peninsula there are three moraines named by Taylor as the Vinemount, Niagara Falls, and Fort Erie Moraines (Chapman and Putnam, 1966). The Vinemount Moraine, composed of Halton Till, is thickest at the base of the escarpment and likely represents the last major stand of the Ontario-centred ice lobe (Sly and Lewis, 1972). This moraine is fairly continuous westward from Grimsby and is probably an extension of the Barre Moraine in New York State (Chapman and Putnam, 1966). The Niagara Falls Moraine forms slight topographic highs through the Haldimand Clay Plain east of Welland, and although it is somewhat discontinuous, it likely represents an extension of the Tonawanda Moraine to the east. The Fort Erie Moraine to the south is not present within the study area.

A number of pro-glacial lakes occurred at different elevations during the deglaciation of Southern Ontario. The Port Huron retreat of the Huron ice lobe is related to glacial lakes in the Erie Basin, namely Lake Maumee at 14,000 yrs. B.P. and Lake Arkona at 13,600 yrs. B.P. (Prest, 1970). At about 13,200 yrs. B.P., a major glacial advance deposited the Port Huron moraine which extended to the southern tip of Long Point in the Erie basin and resulted in the development of Lake Whittlesey in the west end of the basin (Prest, 1970). Fluctuations and later retreat of the ice front allowed this lake to expand to the north and east, forming Lake Warren (12,900 yrs. B.P.) which occupied the entire Erie basin and the southern part of the Huron basin (Prest, 1970). During this period, lake drainage was primarily to the west and south through the Lake Michigan basin. Further recession of both the Huron and Ontario ice lobes resulted in the lower levels of Lake Grassmere, at

640 feet (195 m) a.s.l. and Lake Lundy, at 620 feet (190 m) a.s.l. (Prest, 1970). At these lower elevations, lake discharge was believed to have been eastward for the first time via the south side of the Ontario basin and into the Mohawk and Hudson Rivers system (Prest, 1970).

Early Lake Erie was established by the retreat of the Ontario ice lobe, and at this time only a small part of the Erie basin was occupied by water due to the drainage outlet near Buffalo, New York. However, later differential crustal uplift raised the Buffalo outlet and the Erie basin was filled between 12,500 yrs. B.P. to 12,400 yrs. B.P. (Prest, 1970). As the ice receded eastward from the Ontario basin, Lake Lundy, the first lake in the Ontario basin, was lowered due to the opening of an outlet at Rome, New York and Lake Iroquois was formed at an elevation of 335 feet (102 m) a.s.l. (Prest, 1970). Finally, the ice retreat uncovered the St. Lawrence outlet and the Ontario basin waters drained to a lower level, the Admiralty Phase, which was of short duration and occurred about the beginning of the Holocene at 10,000 yrs. B.P. (Winder, Sanford, and Terasmae, 1975). From this time until about 9,000 yrs. B.P., the water levels in both the Erie and Ontario basins rose to their present elevations (Prest, 1975).

Stream Development in the Niagara Peninsula

The prominent topographic feature of the Niagara Peninsula is the Niagara Escarpment, which may be defined geomorphologically as a cuesta. Above the escarpment, the topography is generally of low relief, except for the Fonthill Kame which reaches an elevation of more than 850 feet (262 m) a.s.l. at its summit. In this area the streams are characterized by shallow channels of low gradients and show very few indications of degradation. Through the escarpment, the streams have eroded V-shaped valleys and change in morphology from channels with small falls and cascades, to boulder beds with riffle and pool sequences. Finally, as they emerge from the base of the escarpment, they develop a pseudo-braided character. Beyond the braided reaches, the streams breach the old Lake Iroquois shoreline and become sinuous to meandering before draining into Lake Ontario.

The time of development of these streams is subject to debate. Sly and Lewis (1972) believe that the streams are either pre- or inter-glacial channels which were exhumed during the moist climatic conditions of pro-glacial Lake Iroquois time. However, Straw (1968) has proposed that only the re-entrant valleys of 12 Mile Creek and in the Dundas area existed prior to the last glacial advance, at which time, their valleys were widened by glacial scour. This belief is based on a number of factors which include the U-shaped form of the re-entrants, the abundance of glacial drift contained within the valleys and the valley orientation which does not generally conform to the direction of the last glacial advance (Straw, 1968). Straw also suggests that smaller streams such as 4 Mile, 15 Mile, 16 Mile, 20 Mile and 40 Mile Creeks are the result of meltwater drainage originating from the retreating Port Huron ice.

The earliest known drainage from the Erie Basin to the Ontario basin was through the pre-late Wisconsin Niagara River via St. Davids Gorge (Hobson and Terasmae, 1969). On the basis of geophysical evidence, palynological correlation and Pleistocene stratigraphy, Hobson and Terasmae (1969), determined that the gorge was eroded during the Plum Point interstadial about 22,800 $\pm$ 450 yrs. B.P. Thus, if the other streams draining the area above the escarpment were initiated prior to the Port Huron advance, they too might contain sediments of Plum Point age. However, their stream valleys contain no sediment older than late Wisconsin (Feenstra, 1972). Also, there are a number of terrace sets in the smaller valleys which may have resulted from the higher flows derived from the drainage of Lake Warren as the Lake Ontario-centred ice lobe retreated. As a consequence, it is believed that the advancing ice created crevasses in the escarpment face and as this same ice lobe retreated, Lake Warren waters drained through these channel-ways and developed degrading streams with V-shaped valleys. The Admiralty low-water phase of the Ontario basin also contributed to the channel development by causing a lower base level which would enhance the degradation ability of these streams.

Isostatic rebound has occurred at the eastern outlet of Lake Ontario since ice retreat and has resulted in a rise of water level at the west end of the lake. It has been determined from sediment and fossil data that the present rate of isostatic uplift is about 1.2 feet (0.35 m) per century at the east end of Lake Ontario (Karrow, Clark and Terasmae, 1961). As a result of the rising base level, gradients have been reduced and baymouth bars and lagoons have formed at the mouths of the streams entering Lake Ontario.

METHODOLOGY

Sediment Sampling Techniques

A total of 59 sediment sampling stations were selected from the streams studied. Sampling stations were chosen both upstream and downstream of waterfalls, log jams and formation contacts, as well as across bars and riffles. Because of the variable distances between these features, the spacing of stations was also variable. The number of sampling stations for each creek are: 15 stations on 15 Mile Creek, 13 stations on 16 Mile Creek, 9 stations on 18 Mile Creek, 12 stations on 20 Mile Creek, and 10 stations on 30 Mile Creek.

At each sampling station, a steel tape was placed across the channel, normal to the flow direction, and 60 pebbles were chosen at pre-determined intervals depending on stream width. The long, intermediate and short axes of each pebble were measured and the sphericity and roundness were determined using a Powers visual chart (Krumbein and Sloss, 1963, p.111). The lithology of each clast was then identified from a fresh surface.

The streams were surveyed, over the entire distance of sediment sampling, using a transit and stadia according to the method outlined by Brinker (1969). The survey generally followed the thalweg, except in flat reaches where it was difficult to distinguish. The positions of the sampling stations were recorded during the survey.

Hydrologic Techniques

A gauging station is located on 20 Mile Creek, slightly upstream of Balls Falls and is shown in figure 5. This station (station number 02HA006) is maintained by the Water Survey of Canada and has been in operation since 1957. Records of average and mean daily discharge, from 1957 to 1975, were obtained from federally-published documents and a continuous flow chart for 1976 was supplied by the Survey at Guelph, Ontario.

Fluorometric techniques were used as a means of analysing the flow along specific reaches of 20 Mile Creek. The basic principle of this method is to inject a fluorescent dye at some known distance upstream of the fluorometer and measure the time-of-travel of the tracer. The advantage of this technique over current meter measurements is that the values obtained represent a modal flow velocity over a reach of the channel rather than the average velocity at a cross-section.

A Turner Model 111 fluorometer was used in this investigation along with Rhodamine B as the dye tracer. This dye was chosen because it is non-toxic, inexpensive, highly soluble and only slightly absorbed by algae and sediment (Buchanana, 1964).

The fluorometer is equipped with two interchangeable doors used for discrete or continuous sampling and a manual adjusting slit which alters the intensity of the ultraviolet light passing through the sample. Prior to field operation, the fluorometer was calibrated using a set of five standards of known concentration (1.0 ppb, 3.0 ppb, 6.0 ppb, 10.0 ppb and 12.5 ppb). The standards were analysed using both doors with variable light intensities as a constant temperature of 20°C. Although the continuous sampling door was used in the field, the fluorometer was calibrated using both doors in order to attain greater accuracy. The results of the analyses are presented in figure 7. The numbers adjacent to each curve indicate the relative light intensities, 30x being the highest. The curves in figure 7 indicate that the standards have higher fluorescence readings in the continuous door because it contains a larger curvette which allows for greater exposure of the sample to ultraviolet light.

The two curves in figure 8 indicate the relation between dye concentration for each door, reduced to a light intensity of 1x. The data for these curves were calculated by dividing the fluorescence readings by the light intensity. The slope for the discrete door was found to be 0.33 and for the continuous door the slope equals 3.3.

Feuerstein and Selleck (1963) have shown that fluorescence intensity increases with decreasing temperature for dilute solutions. This rate of increase is proportional to the type of dye employed. Observed fluorescence values for both standards and natural waters were therefore recalculated using the procedure outlined by Feuerstein and Selleck (1963, p.9, fig. 5). According to Buchanan (1964) natural waters have an inherent fluorescence.

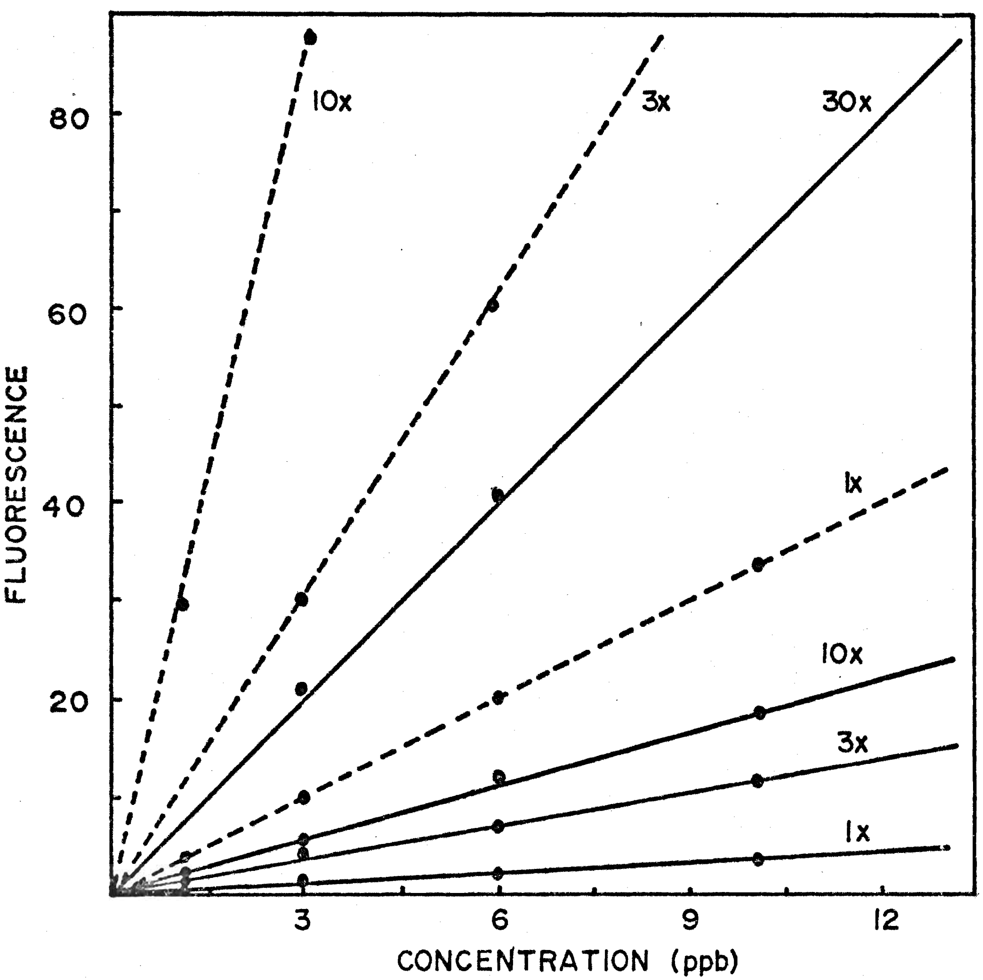

Fig. 8. Calibration curves for discrete and continuous sampling doors.

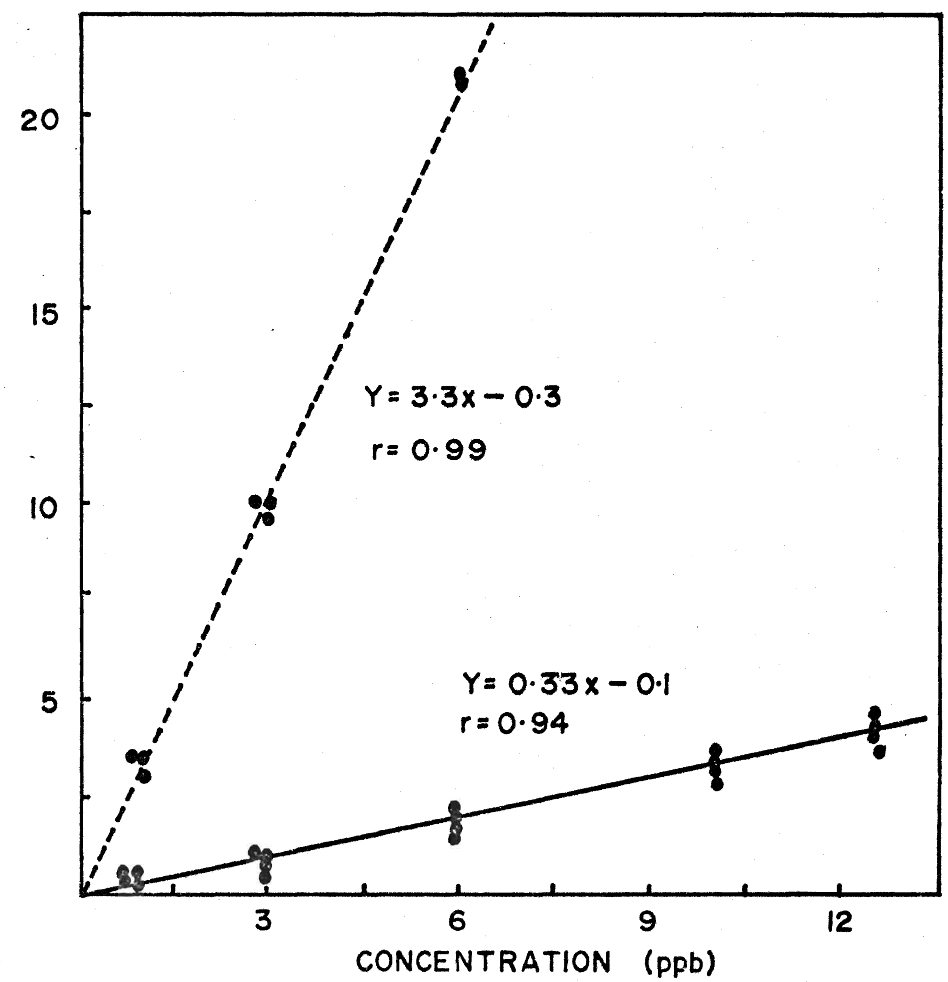

Fig. 9. Standardised curves for discrete and continuous sampling doors.

Thus, background fluorescence must be measured and subtracted from the field data prior to calculating the dye concentration.

Two reaches of 20 Mile Creek were selected for fluorometric studies (fig. 1). The upper reach, located in the vicinity of the Highway 8 bridge, is 354 feet (108 m) in length with an average gradient of 0.0045. The lower reach is 231 feet (70 m) long, with an average gradient of 0.0038 and is located upstream of the lower bridge in the Jordan Valley Campground. Both of the reaches contain at least one pool and riffle sequence.

A gas-powered generator was used in the field as a source of electricity for the fluorometer and waterpump. The amount of dye injected into the stream varied with discharge, turbidity and ice conditions and ranged from 0.5 to 3.0 g. Prior to injecting the dye, the water temperature and background fluorescence were recorded. The dye solution was then injected into the flow at the same location for all runs and the change of fluorescence was monitored. Each run was concluded when the fluorescence values decreased to approximately half that of the peak value. After the completion of a run, the discharge and velocity were measured using a current meter.

SEDIMENT DATA AND RESULTS

Downstream Changes in Sediment Composition

The streams in the study area contain a large volume of coarse sediment originating from the Silurian strata of the Niagara Escarpment. Figures 10 to 14 indicate that sediments derived from eight of the eleven escarpment formations were present in sufficient quantity for analysis. The dominant lithologies, those comprising at least 5 per cent of the samples in most streams, were derived from the following units: Gasport, DeCew, Rochester, Irondequoit, Reynales, Thorold, Grimsby and Whirlpool. Pebbles derived from the two upper members of the Lockport Formation, the Eramosa and Goat Island Members, were present in the channels but in insufficient quantity. Very few Neagha clasts were found because the Neagha Formation is less than 0.5 feet (0.15 m) thick throughout the study area. Sediments originating from the Power Glen Formation only occurred in three samples downstream of Balls Falls on 20 Mile Creek. In the other study reaches the Power Glen Formation is overlain by the Halton Till and therefore, its sediment production is limited.

A miscellaneous category was used in the pebble count to include those lithologies which did not originate from one of the eight dominant source units. Sediments in this category include the previously mentioned sparse lithologies, as well as glacial erratics derived from till in the river banks and shale clasts originating from the Queenston

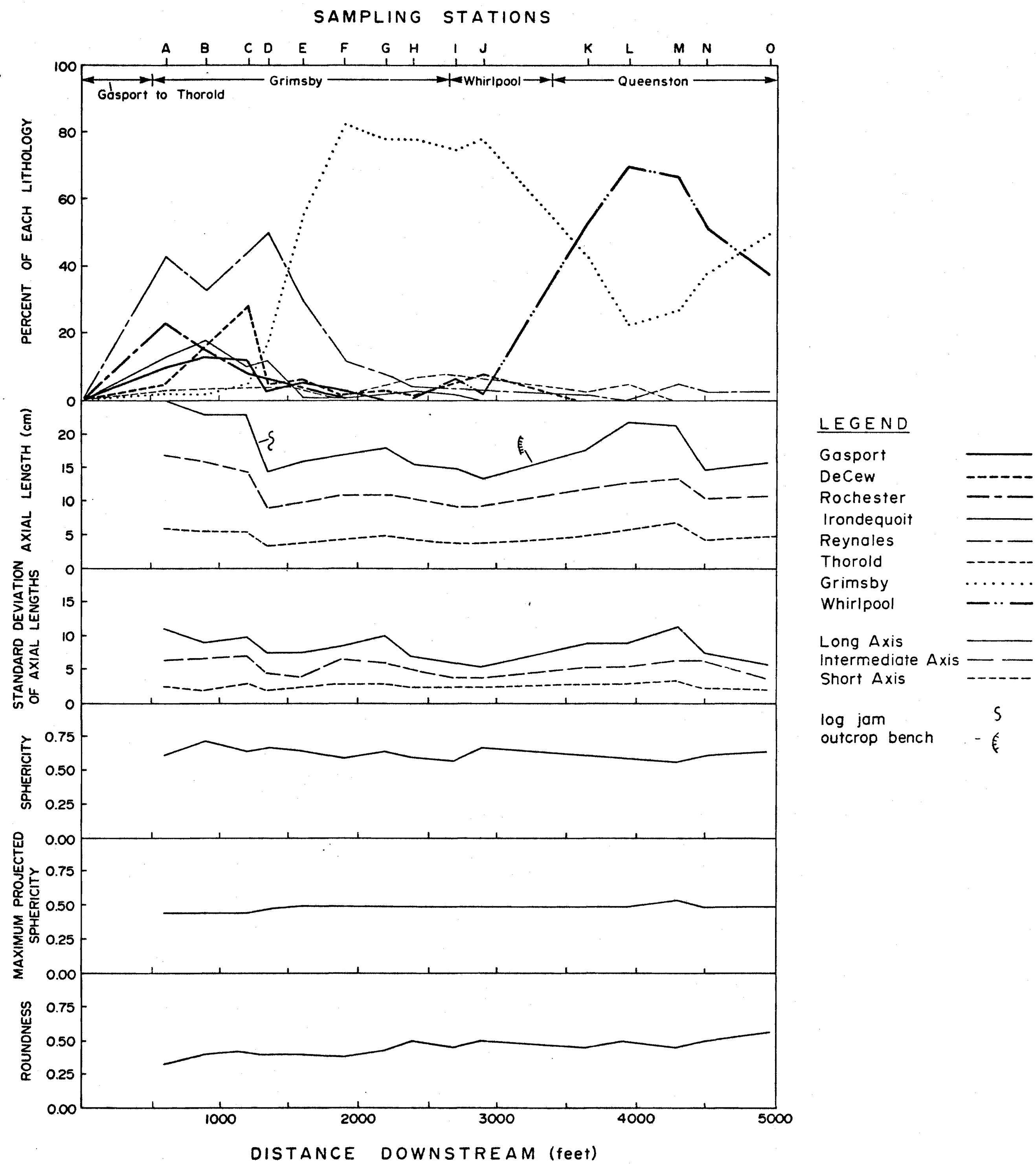

Fig. 10. Sediment characteristics on 15 Mile Creek. (1,000 ft. = 305 m).

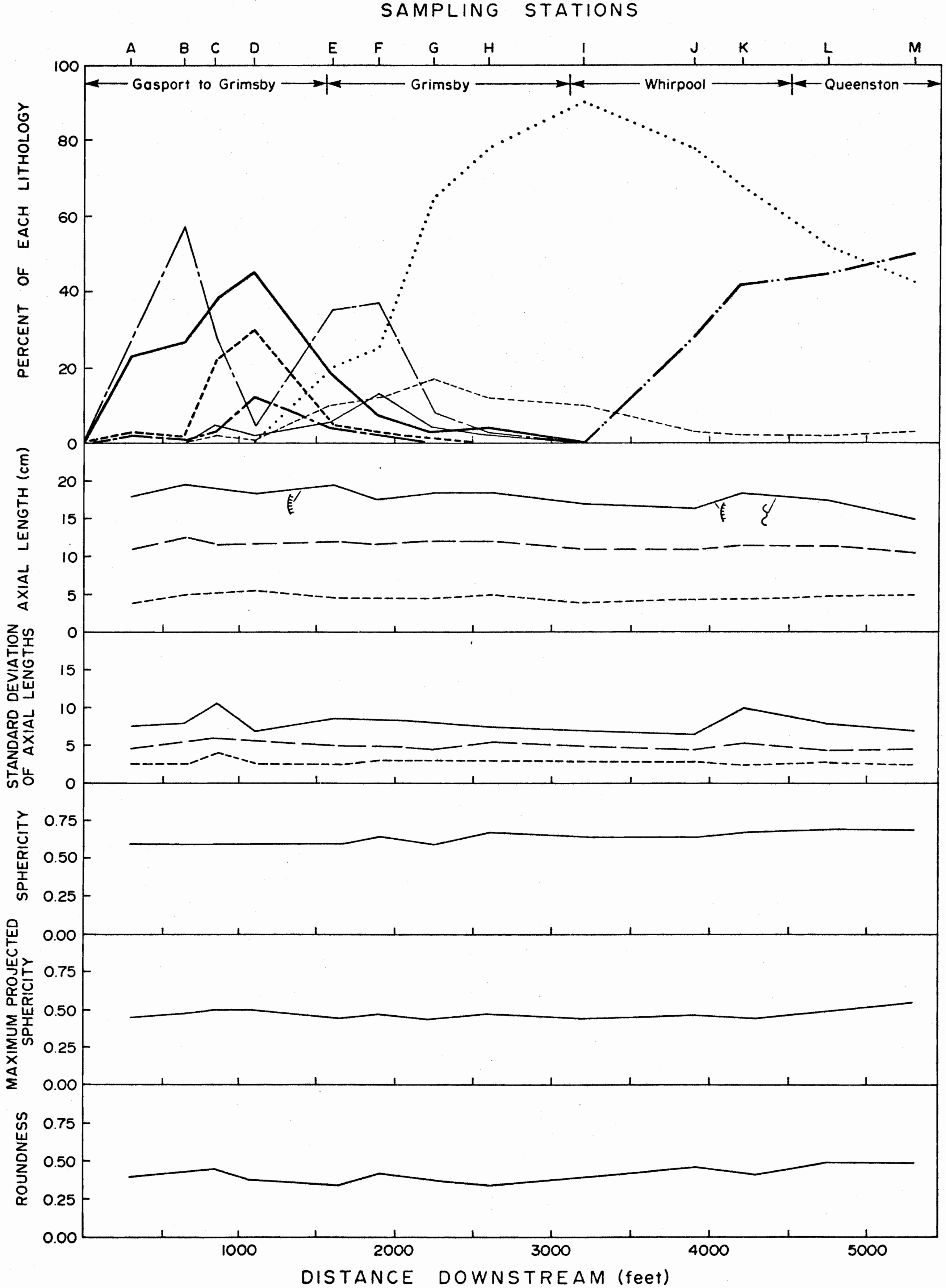

Fig. 11. Sediment characteristics on 16 Mile Creek.

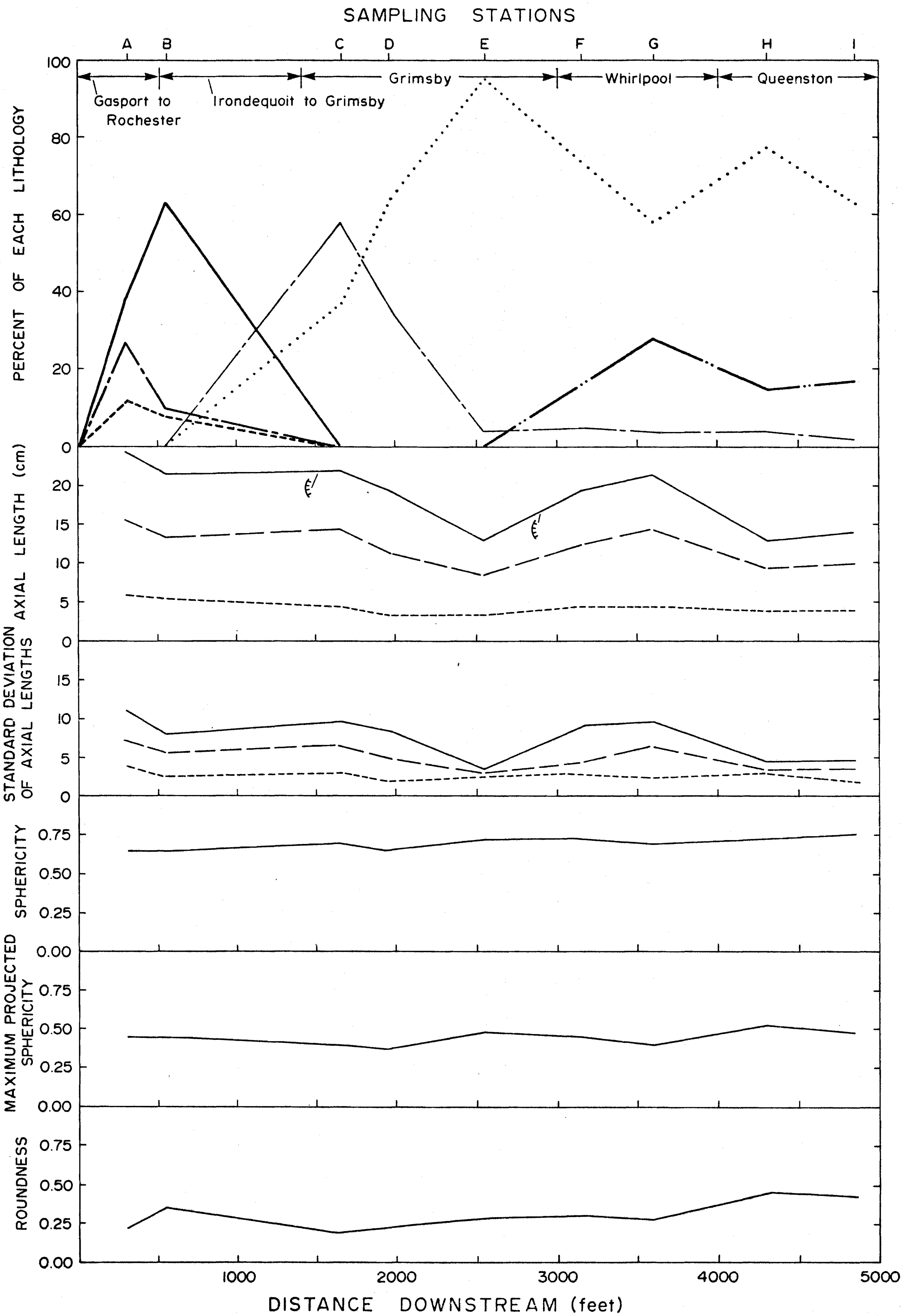

Fig. 12. Sediment characteristics on 18 Mile Creek.

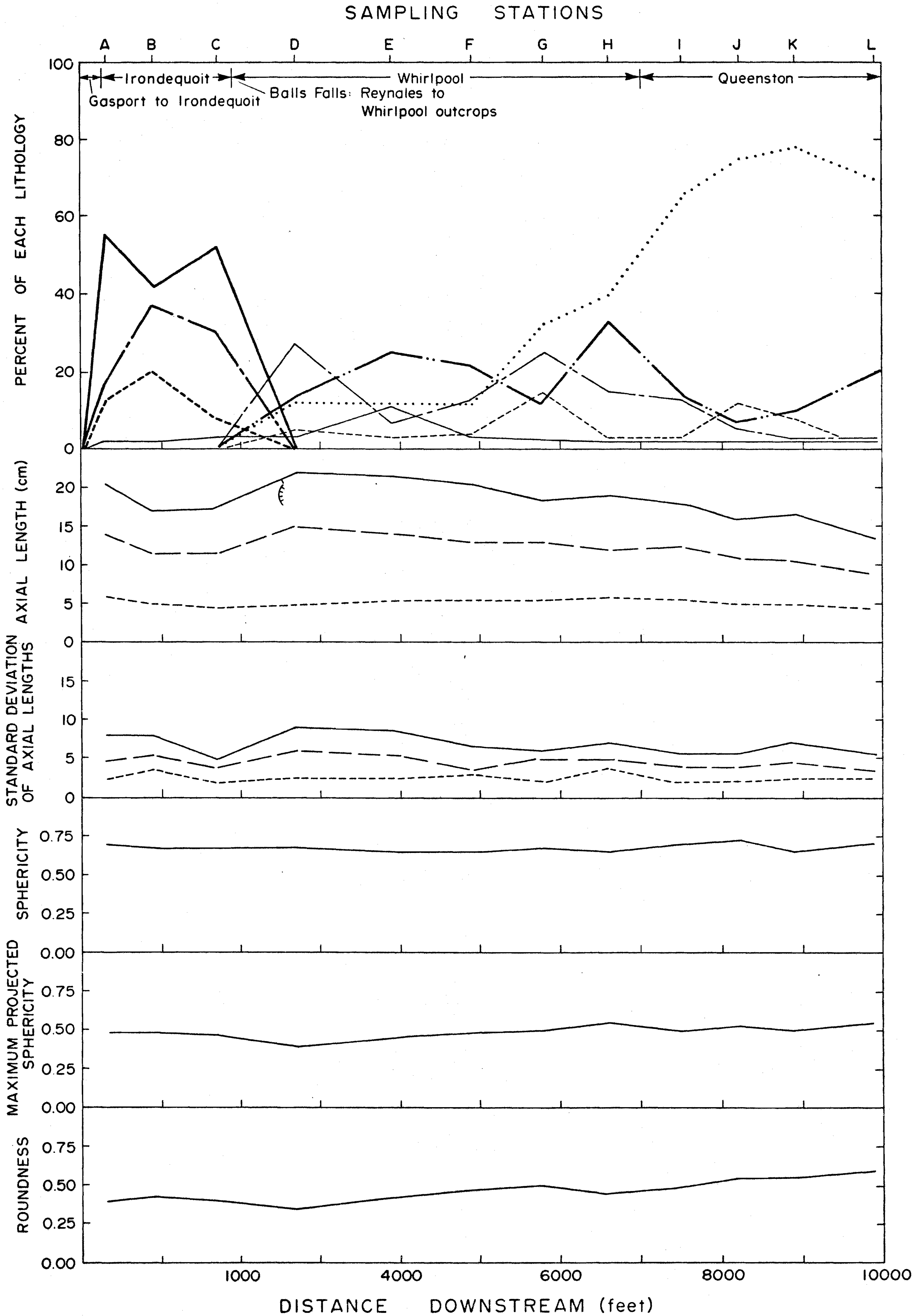

Fig. 13. Sediment characteristics on 20 Mile Creek.

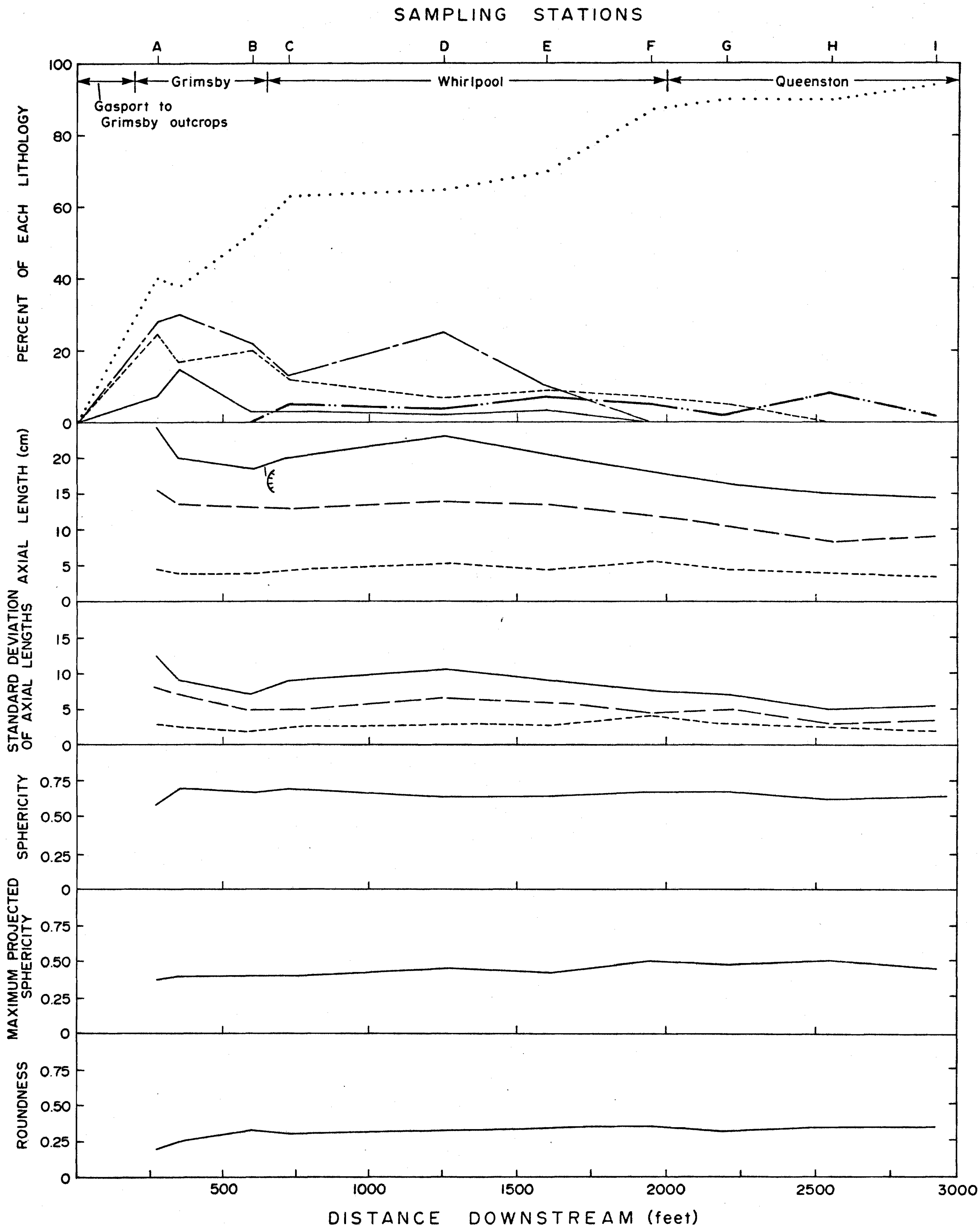

Fig. 14. Sediment characteristics on 30 Mile Creek.

Formation. As a result, the percentage sums of a few samples, particularly those in the lower half of the study reaches, do not total to 100 per cent. It should also be mentioned, that the escarpment formations decrease in thickness and increase in elevation towards Hamilton (Bolton, 1957). These lateral variations cause a decrease in the frequency of clasts derived from the Gasport Member as well as the DeCew and Rochester Formations.

Figures 10 to 14 illustrate the dominance of pebbles originating from the Grimsby, Whirlpool and Reynales Formations. The second most prevalent clast lithologies are those derived from the DeCew Formation and the Gasport Member of the Lockport Formation. Least abundant of the sediments sampled are, in decreasing order, clasts from the Rochester, Irondequoit and Thorold Formations. The relative abundance of these pebble lithologies is a direct result of the thickness of the parent formation in that the five most abundant lithologies correspond to the five formations having the greatest thickness. The Rochester Formation, however, is anomalous in that it is the thickest unit, 40 feet (12.2 m) and is one of the least abundant lithologies. The Rochester Formation does not produce many coarse fragments because it is a shaly unit which produces sediments finer than the size examined in this study.

The Grimsby Formation is the second thickest, 30 feet (9.2 m), unit of the escarpment and as a result its sandstone pebbles dominate the sediments found in the study reaches.

These pebbles reach a maximum of 95 per cent on 18 Mile and 30 Mile Creeks and about 80 per cent on the remaining streams. The diagrams indicate that on 15 Mile, 16 Mile and 20 Mile Creeks, the per cent of Grimsby sediments gradually increases over distances of 1,000 to 2,000 feet (305 to 610 m) before reaching a peak value. On 18 Mile and 30 Mile Creeks the abundance of Grimsby pebbles reaches a maximum frequency over the first 1,000 feet (305 m) of transport. The rate of increase of Grimsby pebbles changes with the outcrop pattern of the units associated with this formation. For example, on 15 Mile, 16 Mile and 20 Mile Creeks, the Grimsby Formation outcrops in waterfalls, together with the Thorold, Reynales and Irondequoit Formations. Consequently, Grimsby fragments gradually increase in percentage as the sediments derived from the other units reach their maxima. However, on 18 Mile and 30 Mile Creeks, this formation outcrops as a separate bench and its sediments reach a maximum immediately downstream of their source.

Sediments originating from the Whirlpool Formation, 15 feet (4.6 m) thick, are the second most dominant lithology. Whirlpool pebbles rapidly increase in frequency over the first 1,000 feet (305 m) of transport. On 15 Mile Creek, they reach a maximum of 70 per cent and on the remaining streams they represent between 30 and 60 per cent of the samples. The Whirlpool Formation outcrops as a separate bench at some distance downstream of the Grimsby sandstone, except on 20 Mile Creek where it outcrops at Balls Falls.

Because this formation is not as thick as the Grimsby Formation, the peak abundance values of its pebbles are usually less than the Grimsby sediments at any given sample location. However, there is a mutual dependence between the abundance of Whirlpool and Grimsby sediments, such that, as the Whirlpool pebbles increase in percentage, the prevalence of Grimsby clasts either increases at a slower rate or decreases. Consequently, the greater sediment production of the Grimsby Formation tends to dominate the abundance of Whirlpool pebbles, except immediately downstream of the Whirlpool outcrop.

The Reynales Formation is about 20 feet (6.1 m) thick throughout the study area and is the greatest producer of carbonate sediments. Peak values of Reynales pebbles are commonly near 45 per cent and the clasts are generally persistent in the channels over distances of 3,000 feet to nearly 7,500 feet (915 m to 2286 m) on 20 Mile Creek. In all streams investigated, the Reynales Formation outcrops with other units. On 15 Mile and 30 Mile Creeks, it occurs as a small bench together with the Gasport and other formations. On 16 Mile, 18 Mile, and 20 Mile Creeks it outcrops in a waterfall with the Irondequoit, Thorold and Grimsby Formations. As a consequence, Reynales clasts tend to slowly increase in abundance as pebbles from stratigraphically higher formations reach their peaks. Fifteen Mile Creek is an exception in that Reynales pebbles reach a maximum immediately downstream of their outcrop because of the slower rate of increase in the frequency of Grimsby clasts.

Sediments originating from the Gasport Member of the Lockport Formation are the second most dominant carbonate clasts. The Gasport dolomitic limestone is about 15 feet (4.6 m) thick along the escarpment, except in the vicinity of 30 Mile Creek where it decreases in thickness to less than 10 feet (3.0 m). Fifteen Mile Creek and 30 Mile Creek have the lowest percentage of Gasport pebbles as a result of the outcrop position of this unit. On 15 Mile Creek, the Gasport Member outcrops upstream of the waterfalls at Rockway, and the downstream movement of its sediments is restricted by the large plunge pool and boulder accumulation below the falls. On 30 Mile Creek, the unit is considerably thinner, higher in elevation, and pebble production is overshadowed by the sediments originating from the Reynales and Grimsby Formations. On 18 Mile and 20 Mile Creeks, the Gasport Member does not outcrop with the Reynales Formation and as a result, these sediments attain maximum frequencies of 63 and 55 per cent, respectively. Sixteen Mile Creek is anomalous in that Gasport sediments reach a maximum of 45 per cent, downstream of the Reynales peak. This is primarily a consequence of two morphological channel features. Firstly, there are no obstructions which might inhibit the downstream transport of Gasport sediments and secondly, because the unit outcrops at the top of a narrow valley, the sediments move downslope into the channel over a distance of some

1,500 feet (460 m).

The downstream variations of Gasport pebbles influence the prevalence of sediments originating from the DeCew and Reynales Formations. The distributions on 15 Mile and 16 Mile Creeks indicate that the frequency of Gasport pebbles causes a double-peak in the Reynales curve. The bimodal curve for the Gasport pebbles on 20 Mile Creek is a function of the peaks of the DeCew and Rochester sediments. Consequently, the Gasport sediments tend to reach their maximum value between 500 and 1,000 feet (162 to 305 m) downstream of their origin, except on 20 Mile Creek where the Gasport Member does not outcrop with the Reynales Formation.

The DeCew Formation is an extremely fine-grained dolostone displaying conchoidal fracture. Throughout the study area, it is approximately 20 feet (6.1 m) thick and usually outcrops with the Gasport Member and Rochester Formation rather than as a separate bench. Pebbles originating from the DeCew Formation generally reach their maximum values within the first 1,000 feet (305 m) downstream of their source. They have peaks of 28 and 30 per cent on 15 Mile and 16 Mile Creeks, respectively. On 18 Mile and 20 Mile Creeks, their peak values are 12 and 20 per cent, respectively. DeCew sediments are absent on 30 Mile Creek because of the limited thickness and higher elevation of the source unit.

Sediments originating from the DeCew Formation have little effect on the frequency of clasts derived from associated units. Its relatively low sediment production is due to the fine-grained texture and conchoidal fracture of this unit. On 15 Mile Creek, however, DeCew pebbles are more abundant than Gasport sediments because the DeCew Formation outcrops at the brink of Rockway Falls, whereas the Gasport Member outcrops at some distance upstream of the falls.

The Rochester Formation is the thickest unit, 40 feet (12.2 m), in the Niagara Escarpment and produces the only dominant shale pebbles found in the reaches studied. Rochester clasts attain a peak value of 37 per cent approximately 1,000 feet (305 m) downstream of its source on 20 Mile Creek. On the reamining streams, the maxima vary between 12 and 27 per cent over distances ranging from 275 feet (84 m) on 18 Mile Creek to 1,000 feet (305 m) on 16 Mile Creek. Rochester pebbles were not found in the samples taken from 30 Mile Creek because of the limited thickness of the unit, less than 10 feet (3.0 m) and because of the dominance of Grimsby pebbles. As previously mentioned, the Rochester Formation is an extremely fissile lithology which does not produce a great deal of coarse clasts. As a result, its pebbles have little effect on the frequency of other lithologies. Rochester pebbles are however, more prevalent than DeCew sediments on 20 Mile Creek and are present in the channel for a distance of 2,500 feet (765 m). The greater downstream persistence of the Rochester pebbles on 20 Mile is a result of the downstream addition of these sediments from the valley walls which are close to the stream banks.

Sediments originating from the Irondequoit and Thorold Formations are the least abundant of all pebble lithologies. Irondequoit pebbles reach a maximum of 18 per cent on 15 Mile Creek, at a distance of 1,000 feet (305 m) downstream of their source. Thorold sandstone clasts attain a peak value of 25 per cent at a distance of 300 feet (92 m) on 30 Mile Creek. Neither of these pebble lithologies were found in the samples taken from 18 Mile Creek because both formations outcrop together with the Reynales and Grimsby Formations which are the dominant sediment producers in this narrow channel. Because these sediments are not very common in the samples, Irondequoit and Thorold pebbles have only a minor effect on the distributions of the more dominant lithologies.

Figures 15 and 16 illustrate the downstream change in frequency of each lithology over the study reaches. The diagrams show that most lithologies reach a maximum frequency within 1,500 feet (457 m) of their source. Grimsby pebbles, however, are an exception and distances to their maxima range from 1,200 feet (365 m) on 18 Mile Creek to 6,400 feet (1952 m) on 20 Mile Creek. These variations result from the changes in outcrop pattern of the Grimsby and stratigraphically associated formations. The data also indicate that the lithologies decrease in abundance at variable rates due to the difference in the distances between the formation

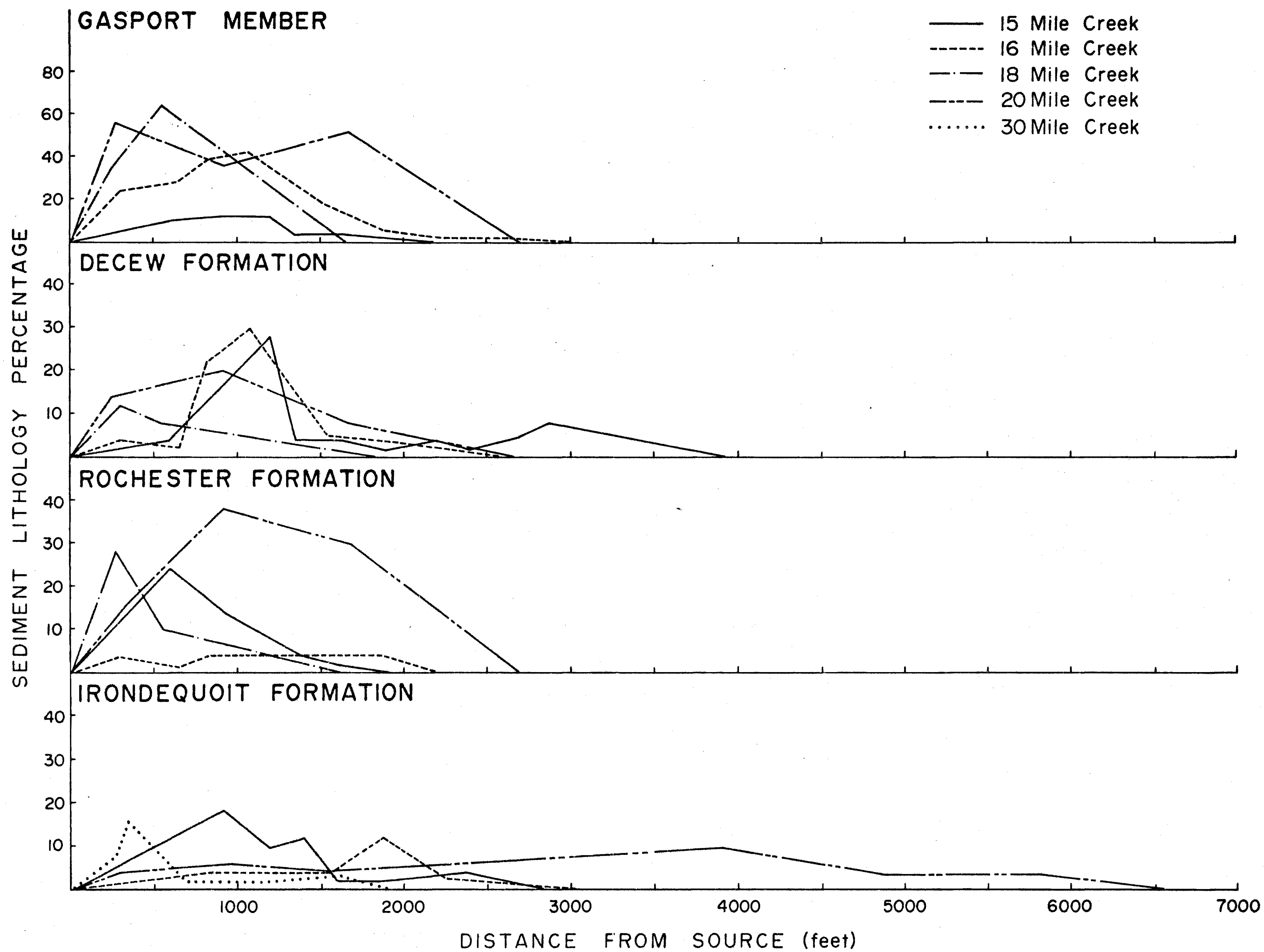

Fig. 15. Downstream variations in the percentage of each lithology. (1,000 ft. = 305 m).

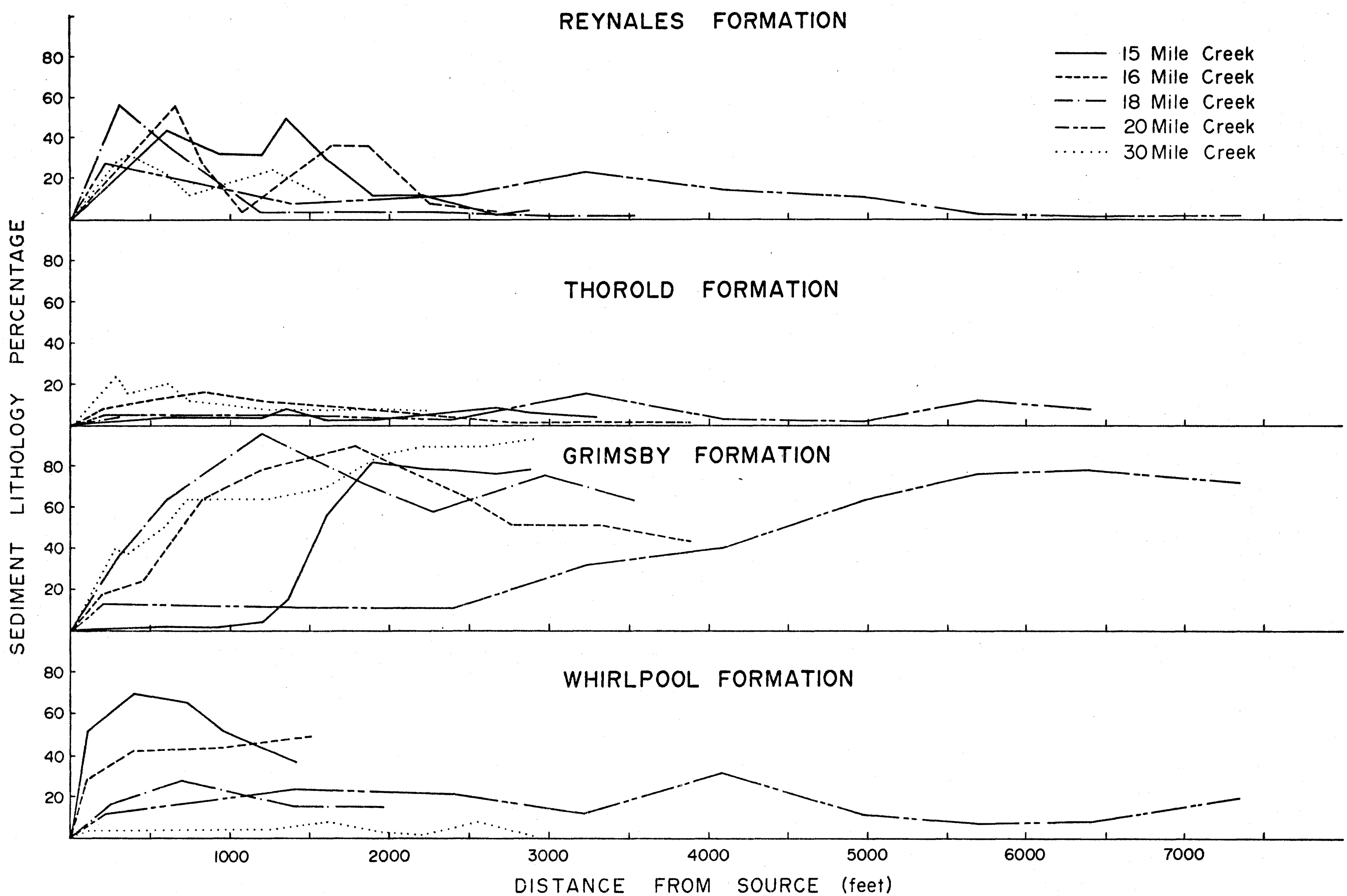

Fig. 16. Downstream variations in the percentage of each lithology.

outcrops. For example, on 18 Mile Creek, the distance between the outcrops of the DeCew and Reynales Formations is about 1,100 feet (335 m) which results in a gradual decrease in the abundance of DeCew sediments. However on 15 Mile Creek, these two formations outcrop within 300 feet (91.5 m) of each other and DeCew sediments rapidly decrease in percentage as Reynales sediments increase in abundance. Finally, it appears that carbonate sediments do not occur over the entire lengths of the reaches because they outcrop upstream of the sandstone units and because their abundance is overshadowed in the downstream sections by the higher frequency of sandstone pebbles.

The preceding discussion has demonstrated that sediment abundance is not entirely dependent on the thickness of the source formation, but also relates to its lithologic properties and outcrop pattern. The distance to the peaks of each lithology is dependent on the outcrop position of the source with respect to associated units. Formations occurring at the upstream ends of cascades or at the brinks of waterfalls, such as the DeCew dolostone, generally peak at a greater distance downstream than those units found at the downstream ends of cascades or at the base of waterfalls, such as the Rochester Formation. The Whirlpool Formation, which outcrops as a distinct bench at some distance downstream of the Grimsby sandstone, reaches its peak abundance value immediately downstream of its outcrop. Thus, the downstream distance to the peak values is influenced by the outcrop position of a given unit and associated formations and suggests that by-passing of lithologies occurs.

The by-passing mechanism of sediment lithologies is well-illustrated at the upper section of 15 Mile Creek. At this reach, the Irondequoit, Reynales, Thorold and Grimsby formations successively outcrop as benches (fig. 2). As downstream distance increases, the pebble lithologies peak in abundance in the same downstream order as the source units appear in outcrop. For example, Reynales pebbles, one of the more abundant lithologies, reach their maximum frequency downstream of the Grimsby Formation as Grimsby clasts gradually increase in abundance to their peak frequency value. Similar examples also occur as sediments from associated units peak in abundance and by-pass material derived from lower units. Pebbles originating from stratigraphically higher units are easily transported across the bedrock surface of the underlying units and accumulate at the base of the lower bench. The by-passing occurs as sediments from the lower unit are transported across the accumulation of sediments derived from the upper unit. Thus, it appears that the outcrop position of the units greatly affects the downstream variation in pebble lithologies.

Downstream Changes in Sediment Size

The coarse sediments found in the channels result from the mechanical and chemical weathering of the bedrock along two, nearly perpendicular, joint planes and along the bedding planes. Sediments are also produced by lateral undercutting where bedrock outcrops in the streams. Because of the physical characteristics of the source formations, the long and intermediate axes of the pebbles produced are usually parallel to the bedding plane, while the short axis is generally normal to this plane.

Figures 10 to 14 illustrate the downstream variations in the average axial lengths for all lithologies combined, as well as the positions of log jams and outcrop benches. The curves indicate that there is a nonsystematic downstream decrease in axial lengths. Sediments are usually coarser upstream of log jams because these obstructions restrict the downstream transport of large fragments, as illustrated at station C on 15 Mile Creek. Downstream of outcrop benches there is also an increase in size due to the influx of coarse material from the outcrop benches. For example, downstream of station J on 15 Mile Creek, axial lengths increase at K and L because these stations are situated downstream of the Whirlpool Formation. In addition, changes in the composition of the bed material also cause variations in sediment size. Axial lengths are usually more variable over sections where large variations in the frequency of pebble lithologies occur, as illustrated on 15 Mile Creek. Field observations also indicate that variations in sediment size are related to the proximity and steepness of the valley walls. Hack (1975) observed that steep valley walls near the channels contribute large volumes of coarse material causing local variations in sediment size.

Linear regression equations and correlation coefficients were calculated for the downstream change in axial lengths for the data in figures 10 to 14 and the results are presented in Table 1. Intercept values correspond to the axial lengths of the sediments of zero transport distance. For each axis, the intercept values are approximately the same on the different streams examined which suggests that sediments derived from the escarpment formations are initially similar in size. Because the axial lengths are controlled by the physical characteristics of the escarpment formations, the similarity of intercept values for each axis implies that the jointing and bedding properties of the units are consistent across the study area. Slope values from the regressions indicate that the long axis decreases more rapidly than the intermediate axis and that downstream changes in the short axis are negligible. Table 1 also shows that slope of regression lines for sediments on 18 Mile and 30 Mile Creeks are greater than those of the other streams. These two streams have the smallest basin areas of those examined, with 6.7 (17.4 km^2) and 4.0 (10.4 km^2) square miles, respectively. As a result, the channel dimensions are less than the other basins and therefore, competence to transport coarse material should be less. Consequently, it is possible that large fragments remain in the upper sections of the channels and are infrequently transported, thus causing a more rapid decrease in size downstream.

Correlation coefficients are highest for the streams (18 Mile and 30 Mile Creeks) that have the least variations in sediment composition and fewest changes in channel

TABLE 1. Linear regression and correlation coefficients for the downstream change in axial lengths (all lithologies combined).

CREEK	STUDY REACH LENGTH in feet (m)	AXES: Long			Intermediate			Short		
		a	b	r	a	b	r	a	b	r
15 Mile	4,350 (1327)	-0.0009	20.7	-0.34	-0.0006	13.3	-0.34	-	4.9	+0.05
16 Mile	5,000 (1525)	-0.0005	19.3	-0.70	-0.0002	11.9	-0.49	-	4.8	-0.08
18 Mile	4,500 (1373)	-0.0020	23.7	-0.72	-0.0009	14.6	-0.60	-0.0003	5.2	-0.61
20 Mile	9,700 (2959)	-0.0005	20.8	-0.60	-0.0003	13.8	-0.61	-	5.3	-0.15
30 Mile	2,750 (839)	-0.0029	23.5	-0.78	-0.0020	15.1	-0.86	-0.0001	4.5	-0.15

NOTE: a slope
b y-intercept
r correlation coefficient
(absent values indicate no slope)

morphology. As previously illustrated on 15 Mile Creek, these factors cause large variations in axial lengths, thus reducing the correlation between axial lengths and distance.

Figures 10 to 14 also illustrate the downstream changes in the standard deviations of the axial lengths for all lithologies combined. The standard deviations represent a measure of size sorting. Because there are only small variations in the specific gravity of the escarpment formations (American Falls International Board, 1974) this parameter should not affect the sorting. The standard deviations are relatively high (about 10 cm) in the upstream sections of the study reaches, indicating that the material is badly sorted which, according to Morisawa (1968), is a common characteristic of coarse sediments. With increasing distance, the values decrease in a nonsystematic fashion, similar to the decrease in axial lengths. The downstream variations reflect the changes in channel morphology and frequency of pebble lithologies. Sorting increases downstream of log jams, due to the deposition of coarser material upstream of the obstructions and is poor downstream of outcrop benches because of the influx of large fragments. Samples containing a large percentage of a particular lithology are usually better sorted than samples with a variety of pebble lithologies.

At the farthest downstream sampling stations, the length of each of the long, intermediate and short axis is approximately the same. In addition, the standard deviations for the three axes have decreased indicating that the sediments are better sorted than farther upstream. It is, however, difficult from this data to establish whether the decrease in sediment size is a result of sorting or abrasion.

The downstream changes in the average axial lengths for each lithology over each stream are shown in figures 17 to 24. The long axis has the greatest decrease while the short axis changes the least. Sediments which are poorly represented in the samples, such as the Rochester, Thorold and Irondequoit, or those which have been derived from coarse-grained, porous units such as the Gasport and Irondequoit have large downstream variations in axial lengths. The diagrams also indicate that for an individual lithology within a stream, the long and intermediate axes tend to have parallel changes while variations in the short axis appear to be independent. Coincident downstream changes in length were recorded for each lithology at successive downstream sampling stations. In approximately 87 per cent of the cases, the long and intermediate axes have parallel changes indicating a simultaneous behavior due to isotropic resistance to abrasion parallel to the bedding plane or a sorting phenomenon.

Linear regressions and correlation coefficients were obtained for the data in figures 17 to 24 and the results are presented in Table 2. Histograms of the intercepts, slopes, and correlation coefficients are shown in figure 25.

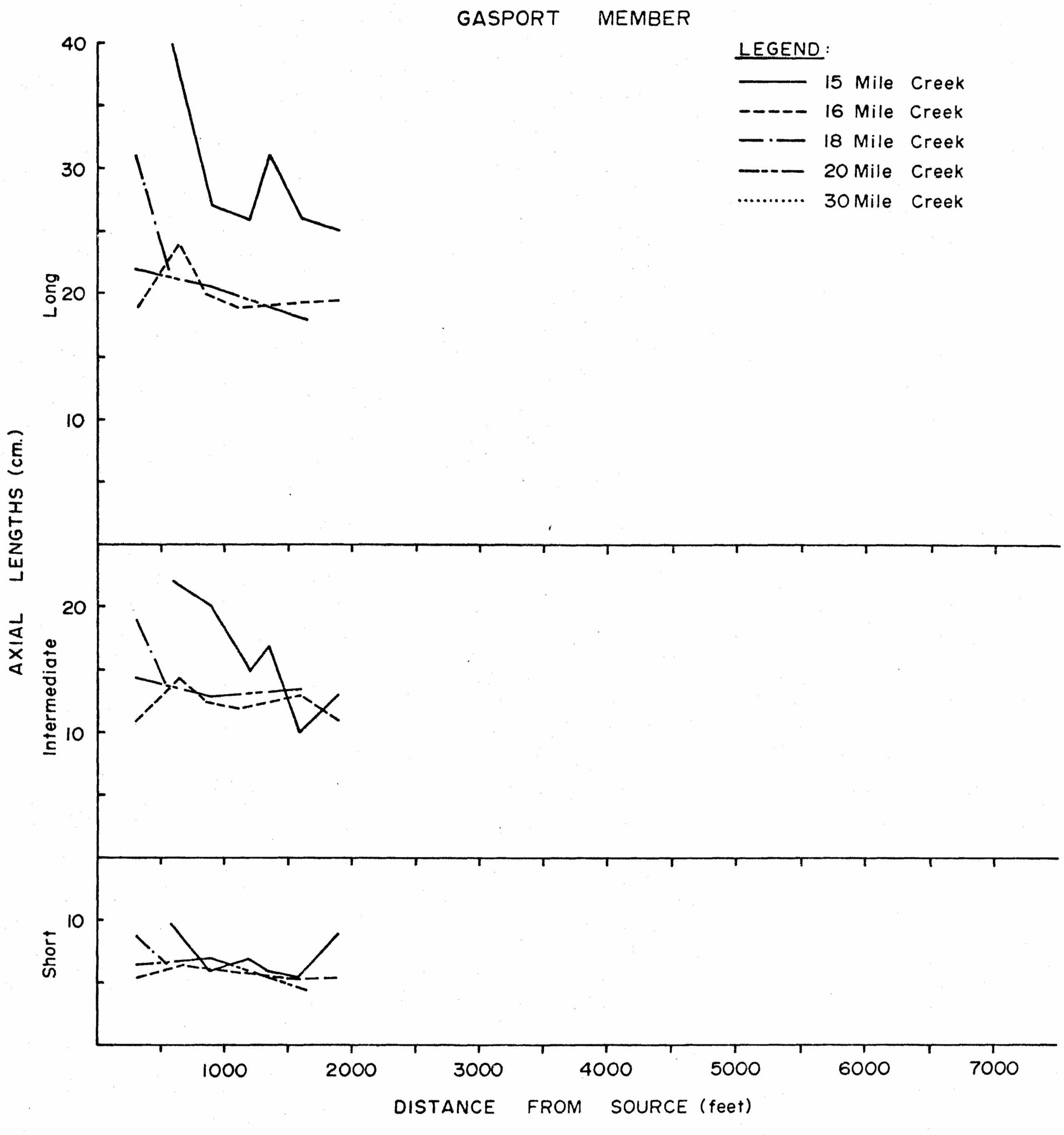

Fig. 17. Downstream changes in axial lengths - Gasport Member. (1,000 ft. = 305 m).

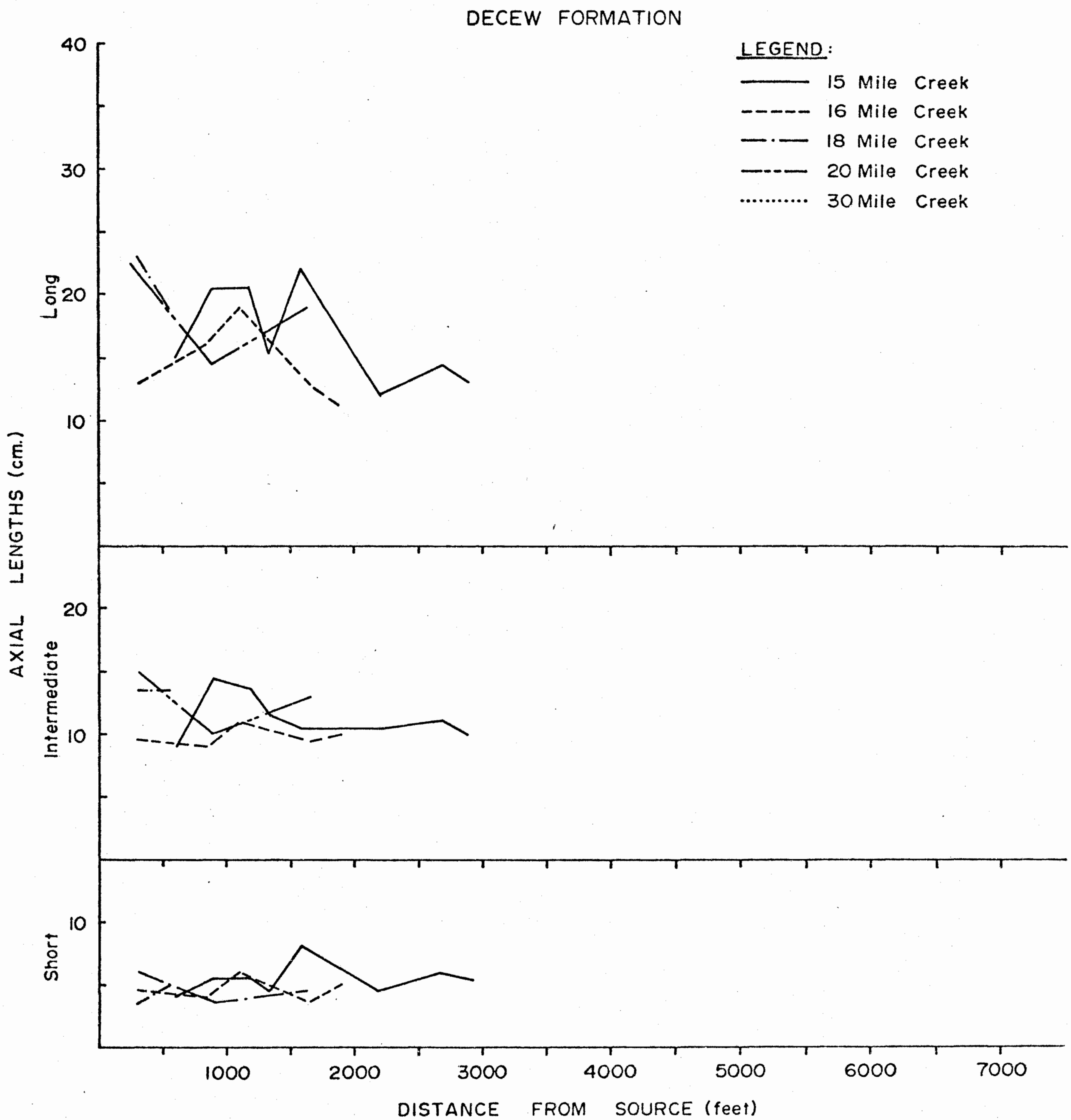

Fig. 18. Downstream changes in axial lengths - DeCew Formation.

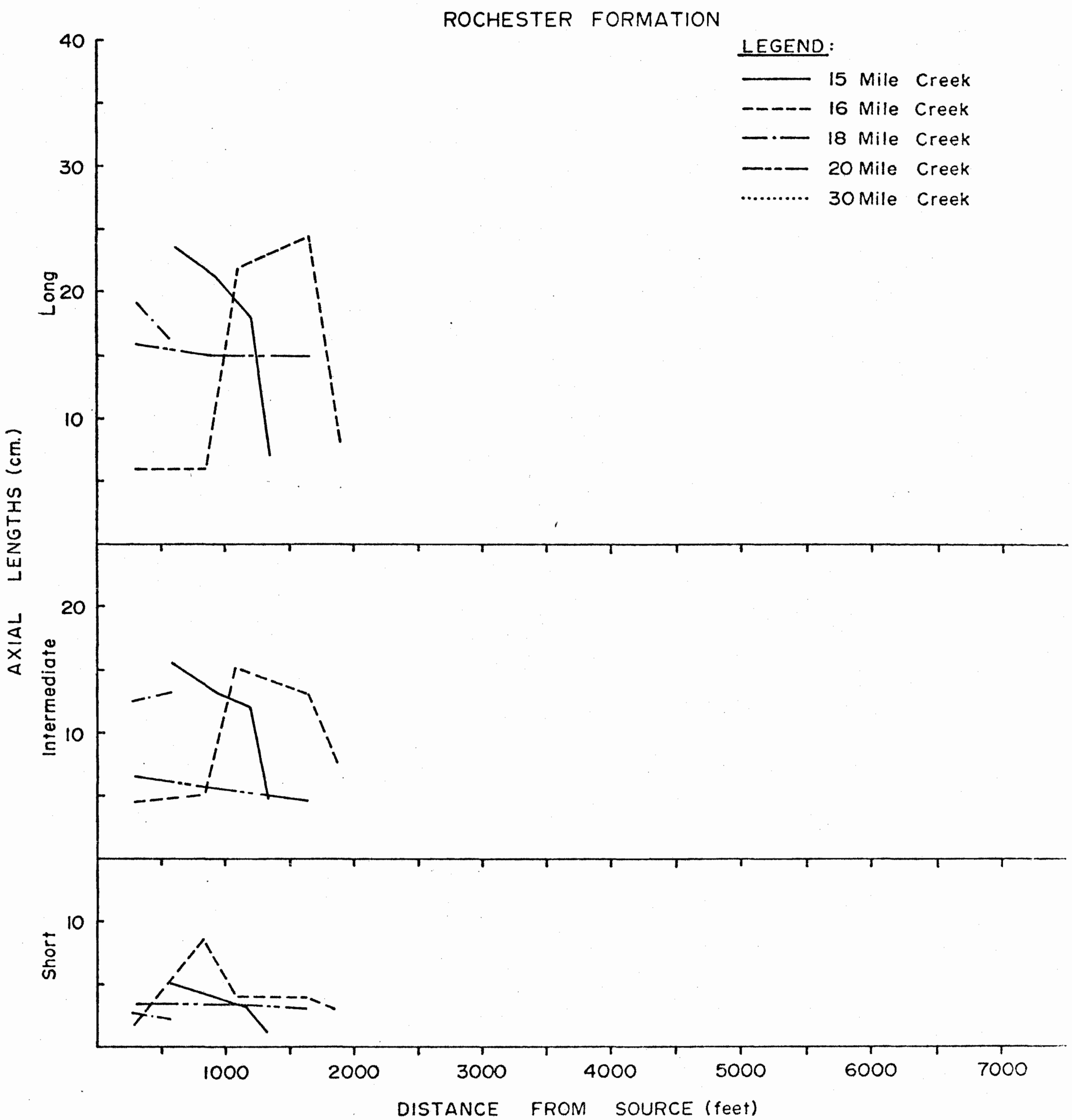

Fig. 19. Downstram changes in axial lengths - Rochester Formation.

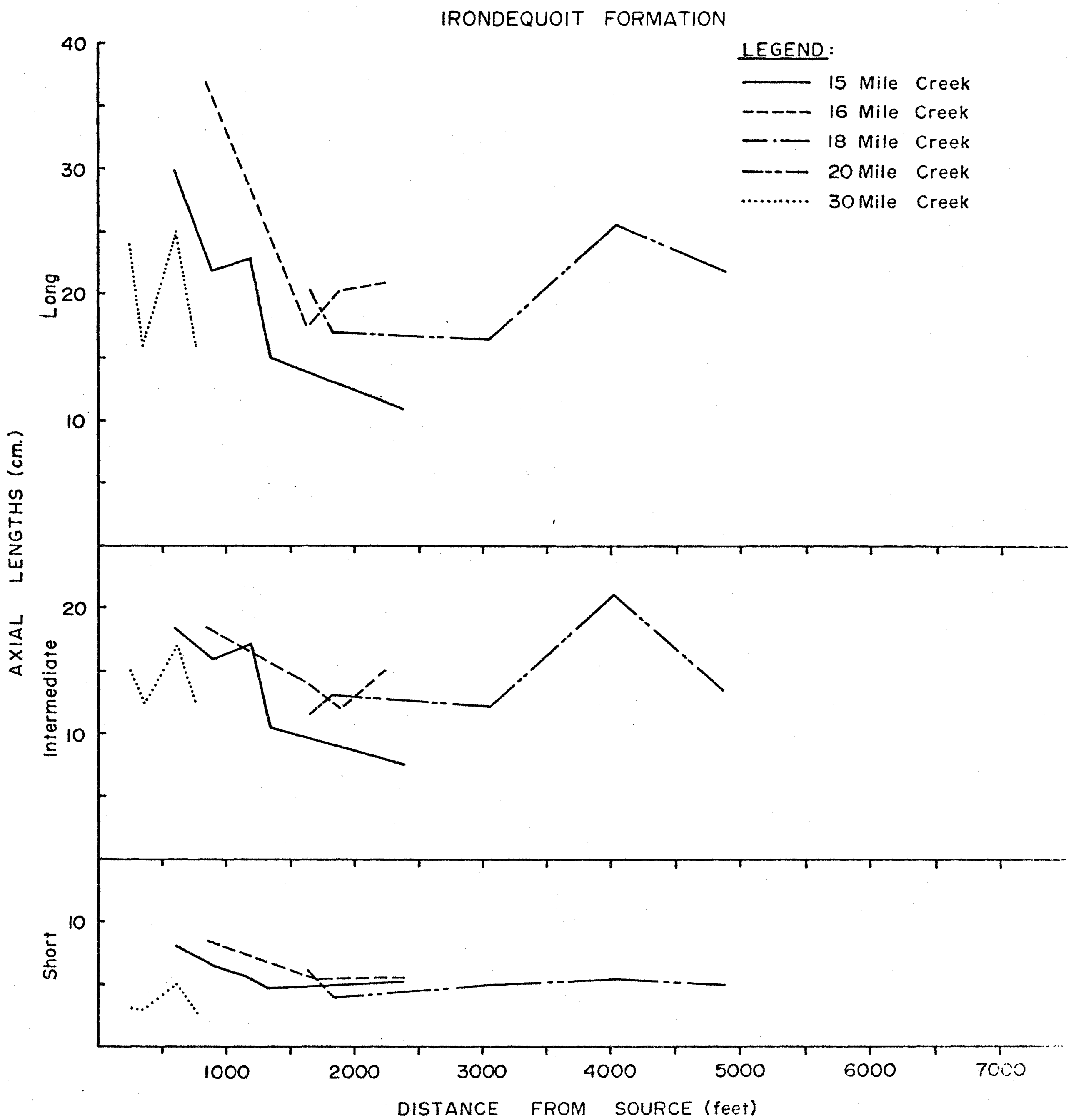

Fig. 20. Downstream changes in axial lengths - Irondequoit Formation.

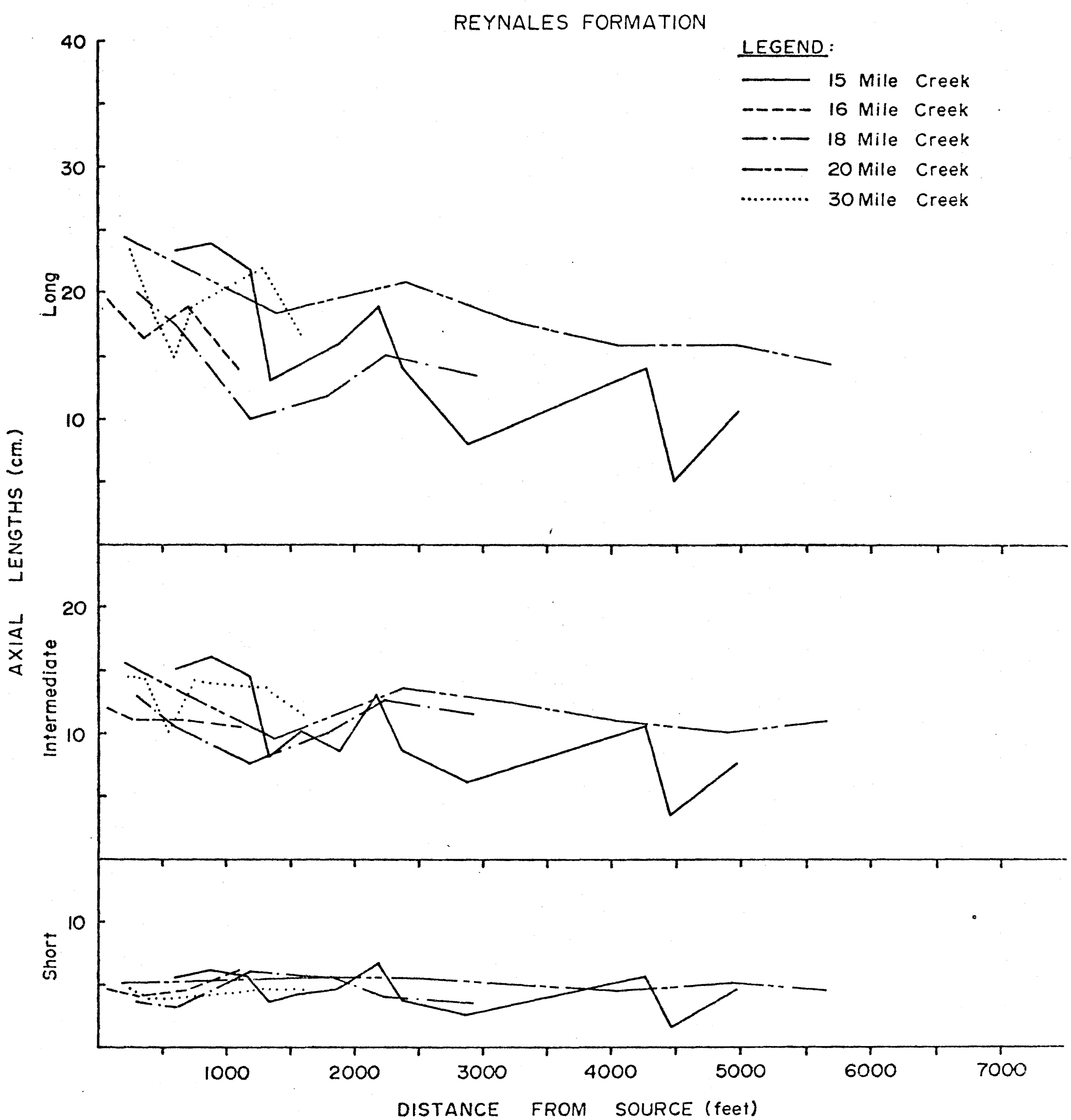

Fig. 21. Downstream changes in axial lengths - Reynales Formation.

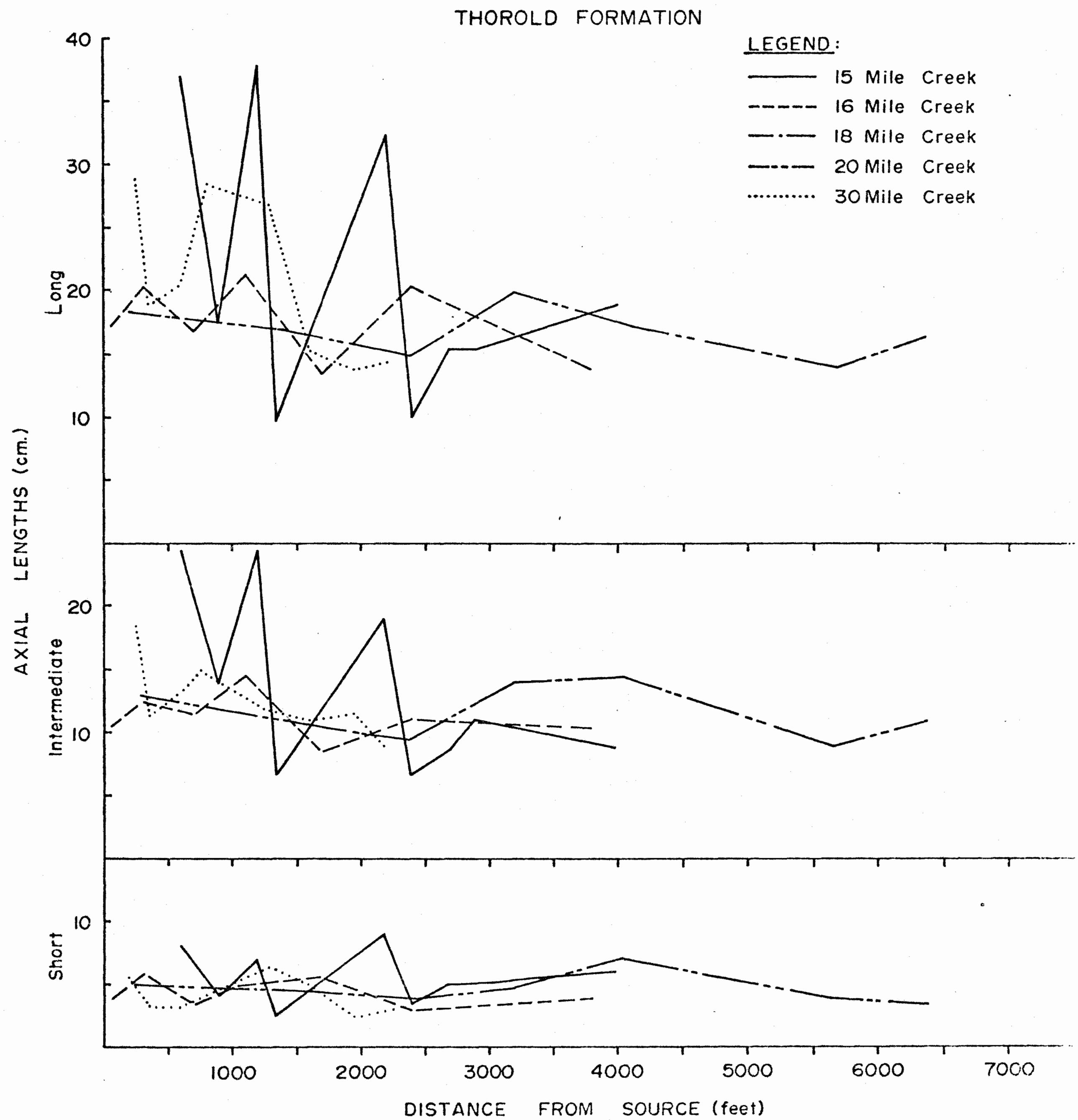

Fig. 22. Downstream changes in axial lengths - Thorold Formation.

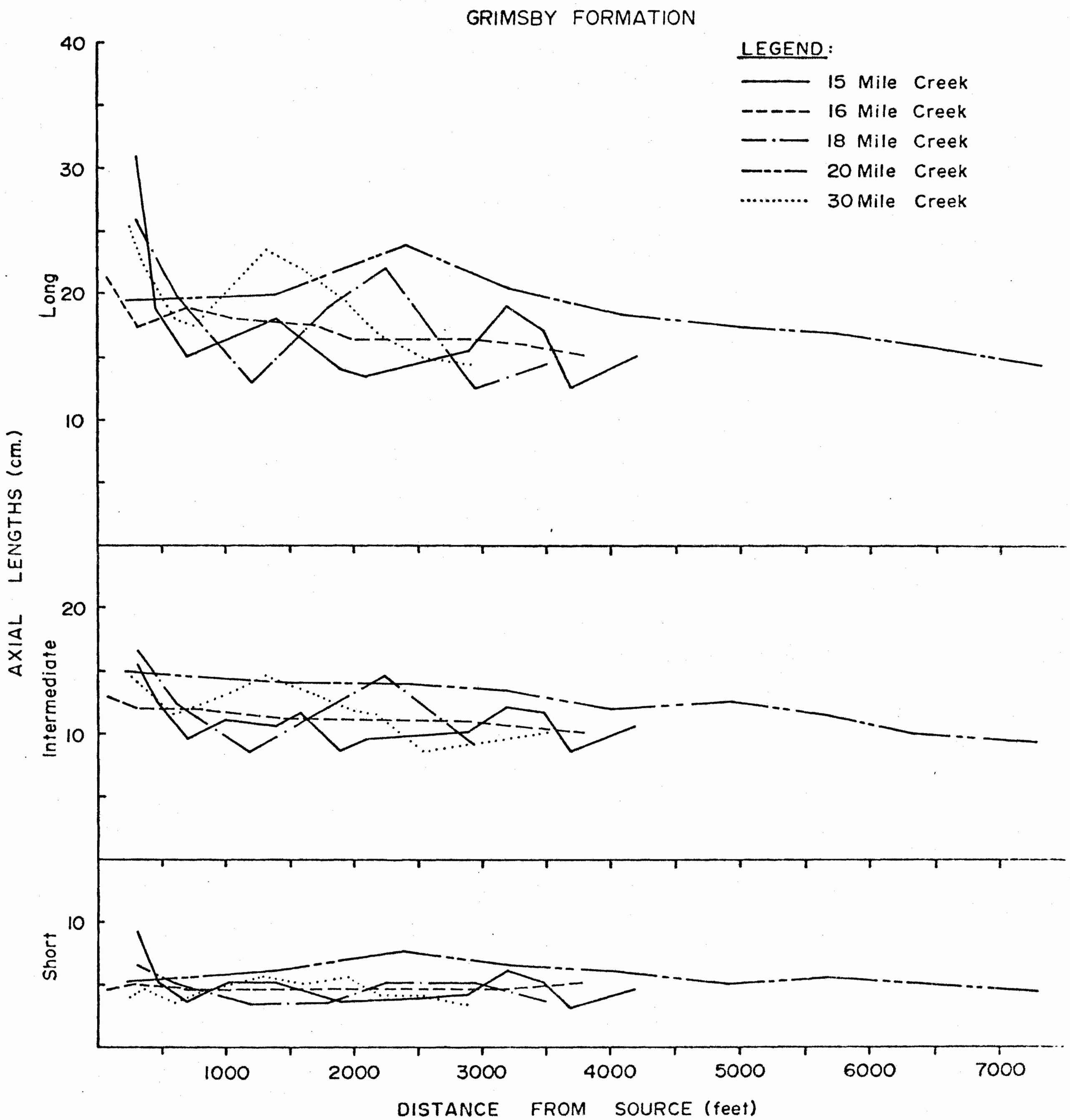

Fig. 23. Downstream changes in axial lengths - Grimsby Formation.

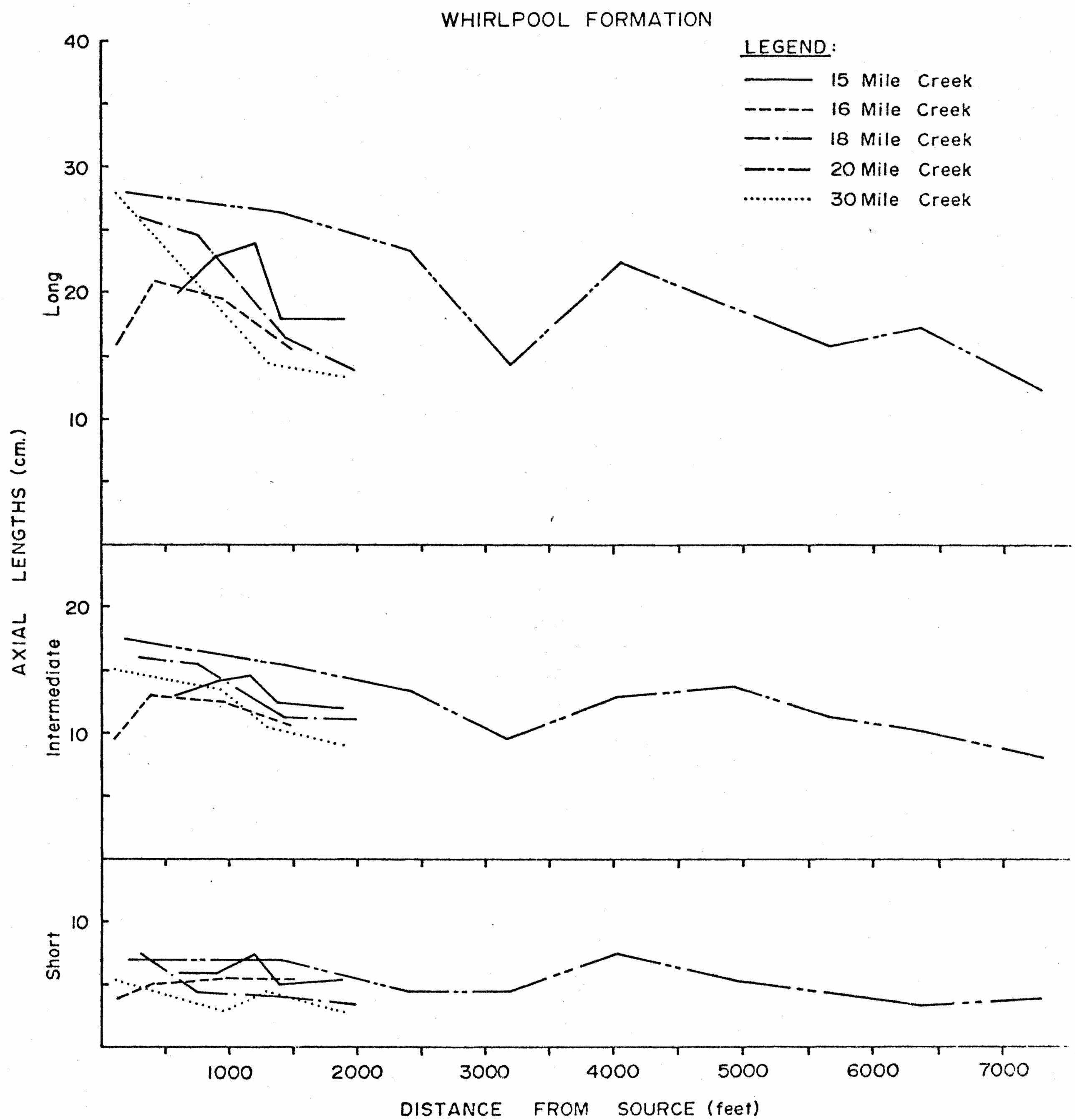

Fig. 24. Downstream changes in axial lengths - Whirlpool Formation.

TABLE 2. Linear regression and correlation coefficients for the downstream change in axial lengths (individual lithologies).

Formation	Creek	n	Long Axis a	Long Axis b	Long Axis r	Intermediate Axis a	Intermediate Axis b	Intermediate Axis r	Short Axis a	Short Axis b	Short Axis r
Gasport (carb)	15 Mile	6	-0.0092	40.7	-0.74	-0.0084	26.8	-0.89	-0.0006	8.0	-0.17
	16 Mile	6	-0.0030	23.8	-0.69	-0.0020	14.7	-0.69	-0.0009	7.1	-0.98
	20 Mile	3	-0.0025	22.4	-0.99	-0.0013	14.6	-0.84	-0.0009	7.0	-0.76
Irondequoit (carb)	15 Mile	5	-0.0098	32.9	-0.90	-0.0062	21.9	-0.91	-0.0015	7.6	-0.72
	16 Mile	4	-0.0124	44.7	-0.84	-0.0030	19.9	-0.70	-0.0026	10.2	-0.96
	20 Mile	5	-0.0021	22.2	-0.72	-0.0001	12.4	-0.13	-0.0000	4.8	-0.02
DeCew (carb)	15 Mile	8	-0.0040	24.1	-0.77	-0.0020	14.9	-0.82	+0.0002	5.3	+0.10
	16 Mile	5	-0.0064	23.6	-0.85	-0.0001	10.0	-0.07	-0.0001	4.5	-0.04
	20 Mile	3	-0.0028	21.5	-0.44	-0.0013	13.7	-0.36	-0.0012	5.9	-0.68
Reynales (carb)	15 Mile	12	-0.0031	22.8	-0.77	-0.0018	14.4	-0.68	-0.0004	5.4	-0.44
	16 Mile	7	-0.0013	19.2	-0.49	-0.0004	11.6	-0.32	-0.0005	4.8	-0.42
	18 Mile	6	-0.0020	17.8	-0.55	-0.0001	10.7	-0.13	+0.0001	3.5	+0.20
	20 Mile	7	-0.0016	23.3	-0.90	-0.0005	13.6	-0.52	-0.0001	5.3	-0.52
	30 Mile	6	-0.0028	22.8	-0.60	-0.0021	15.4	-0.93	-0.0002	4.4	-0.15
Rochester (sh)	15 Mile	4	-0.0190	36.7	-0.86	-0.0125	24.0	-0.87	-0.0046	7.9	-0.91
	16 Mile	5	+0.0060	6.3	+0.41	+0.0034	5.0	+0.45	+0.0001	3.7	+0.07
	20 Mile	3	-0.0009	16.1	-0.87	-0.0016	12.1	-0.99	-0.0001	3.4	-0.99
Thorold (ss)	15 Mile	9	-0.0040	29.8	-0.40	-0.0045	23.6	-0.58	-0.0001	5.8	-0.05
	16 Mile	7	-0.0010	19.2	-0.42	-0.0005	12.0	-0.31	-0.0003	4.9	-0.39
	20 Mile	7	-0.0005	18.6	-0.49	-0.0002	12.3	-0.21	-0.0001	4.8	-0.10
	30 Mile	8	-0.0057	27.5	-0.69	-0.0030	16.1	-0.75	-0.0007	4.9	-0.40

TABLE 2 (con't)

Formation	Creek	n	Long Axis a	b	r	Intermediate Axis a	b	r	Short Axis a	b	r
Grimsby (ss)	15 Mile	13	-0.0017	20.7	-0.48	-0.0006	12.0	-0.38	-0.0004	5.6	-0.35
	16 Mile	9	-0.0013	19.6	-0.85	-0.0007	12.5	-0.96	-0.0000	4.5	-0.02
	18 Mile	7	-0.0026	22.8	-0.63	-0.0012	14.0	-0.51	-0.0004	4.9	-0.48
	20 Mile	9	-0.0009	22.2	-0.77	-0.0008	15.6	-0.96	-0.0001	6.0	-0.29
	30 Mile	10	-0.0029	23.7	-0.73	-0.0012	14.8	-0.79	-0.0001	4.6	-0.08
Whirlpool (ss)	15 Mile	5	-0.0028	24.0	-0.51	-0.0011	14.5	-0.61	-0.0004	6.5	-0.22
	16 Mile	4	-0.0050	23.5	-0.96	-0.0021	14.3	-0.91	-0.0003	5.5	0.00
	18 Mile	4	-0.0077	28.8	-0.97	-0.0034	17.1	-0.91	-0.0020	7.0	-0.86
	20 Mile	9	-0.0020	27.7	-0.86	-0.0010	16.6	-0.81	-0.0004	6.9	-0.64
	30 Mile	4	-0.0089	27.9	-0.96	-0.0037	16.1	-0.93	-0.0010	5.2	-0.70

NOTE:
carb: carbonate sediments
sh: shale sediments
ss: sandstone sediments
ns: number of sample points
a: slope
b: y-intercept
r: correlation coefficient

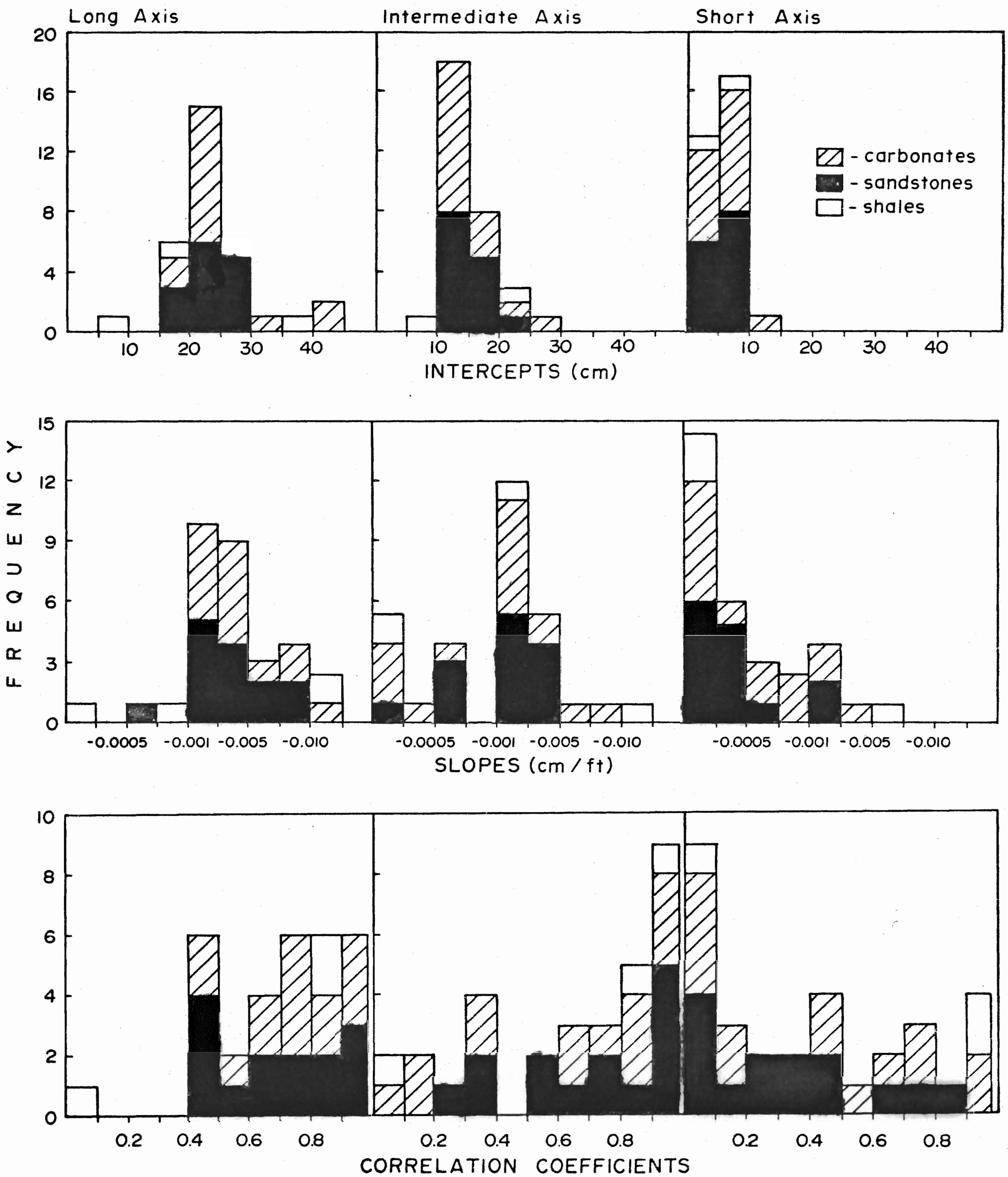

Fig. 25. Histograms of the slopes, intercepts and correlation coefficients from regression analyses.

The histograms of the intercepts indicate an equal number of carbonate and sandstone sediments within the different classes for the three axes. This similarity suggests that the axial lengths are not dependent on the inherent physical characteristics of the source formations, but are more likely a function of the overall joint pattern in the escarpment. The small range of intercept values for the short axis indicates that the majority of the beds within the escarpment formations are less than 10 cm in thickness, regardless of lithology.

Histograms of the slopes indicate that 90 per cent of the values for the long axis and 65 per cent of the values for the intermediate axis are greater than -0.001. The greater frequency of high slope values for the long axis indicates that they decrease at a faster rate than the intermediate axis. The number of carbonate and sandstones within the classes suggests that both lithologies decrease in size at similar rates. Slope values for the short axis are much lower than those of the other two axes due to increased internal resistance to abrasion perpendicular to the bedding plane. Table 2 also indicates that coarse-grained, fossiliferous sediments derived from the Gasport and Irondequoit units have a greater range of slope (-0.0021 to -0.0124), than material derived from fine-grained, well-indurated formations, such as the DeCew and Reynales (-0.0013 to -0.0064). This larger downstream variation in axial lengths likely results from the fissility of the Gasport and Irondequoit sediments due to their coarse-grained, porous and fossiliferous nature.

Histograms of the correlation coefficients between the change in axial lengths with distance indicate that for the long and intermediate axes, approximately half of the values (52 and 48 per cent, respectively) are greater than 0.70. The remaining lower correlation coefficients are generally associated with those lithologies which are poorly represented in the samples. Only 35 per cent of the values for the short axis are greater than 0.70 as this axis changes only slightly with distance.

The previous discussion has shown that the nonsystematic downstream variations in axial lengths, for all lithologies combined, result from changes in channel morphology and variations in the frequency of pebble lithologies sampled. The regression analyses indicate that the initial long and intermediate axial lengths depend on the vertical jointing in the source units and the short axial lengths are controlled by the bedding thickness of the formations from which the pebbles have been derived. The long axis decreases in length at a faster rate than the intermediate axis, while the rate of decrease of the short axis is negligible. Because sediment size is affected by channel morphology and pebble lithology frequencies, size sorting is also influenced by these factors. Samples located downstream of outcrop benches are usually poorly sorted, while sediments downstream of log jams are generally better sorted than the material upstream of these obstructions. Samples comprised of a dominant lithology are usually better sorted than those containing a number of lithologies.

Analyses of downstream variations in the axial lengths of individual lithologies indicate that the changes in the long and intermediate axes are usually coincident, whereas changes in the short axis appear to be independent. It was also determined that carbonate and sandstone pebbles decrease in size at approximately the same rate and that coarse-grained, fossiliferous lithologies have a greater range of slope values than fine-grained sediments. Correlation coefficients suggest that there is generally a good relation between distance and the decrease in the length of the long and intermediate axes, while there is a poor correlation for the downstream change in the short axis.

Downstream Change in Sediment Sphericity and Roundness

Pebble sphericity and roundness were measured in the field by means of a visual comparison chart (Krumbein and Sloss, 1963, p.111). Although such charts are subjective and tend to result in an operator bias, measurements made by the same observer reduce the variability of the results (Griffiths, 1957). Successive downstream measurements of pebble sphericity and roundness were not influenced by the values obtained at the previous section because lithology was not determined until after these measurements had been made. Consequently, this procedure eliminated the bias which may have reuslted from expecting increasing values for a given lithology in the downstream direction.

Figures 10 to 14 show the downstream change in average sphericity, maximum projection sphericity and roundness for all lithologies combined over each stream studied. The curves indicate that visual sphericity is more variable than the other two parameters, although the variations are only minor. There is only a slight sphericity increase of 0.02 between the first and last samples. Because visual sphericity is an estimate, based on the examination of the intermediate long axial ratio, its downstream variability is directly related to the downstream changes in axial lengths. The maximum projection sphericity, developed by Sneed and Folk (1958), remains nearly constant downstream. Pebble roundness has an average increase of 0.16 between the first and last samples and is intermediate in variance between the two sphericity parameters. Because curves for these parameters represent averages for all lithologies combined, it is likely that this has resulted in an homogenizing effect of the values and consequently only minor downstream fluctuations occur.

Figures 26 to 33 illustrate the downstream variations in the average sphericity, maximum projection sphericity and roundness of each lithology over the reaches studied. Linear regressions and correlation coefficients were derived for the downstream change in textural characteristics and the results are presented in Table 3. The average initial sphericity, represented by the intercepts from the regressions, for carbonate sediments (Gasport, Irondequoit, DeCew, Reynales)

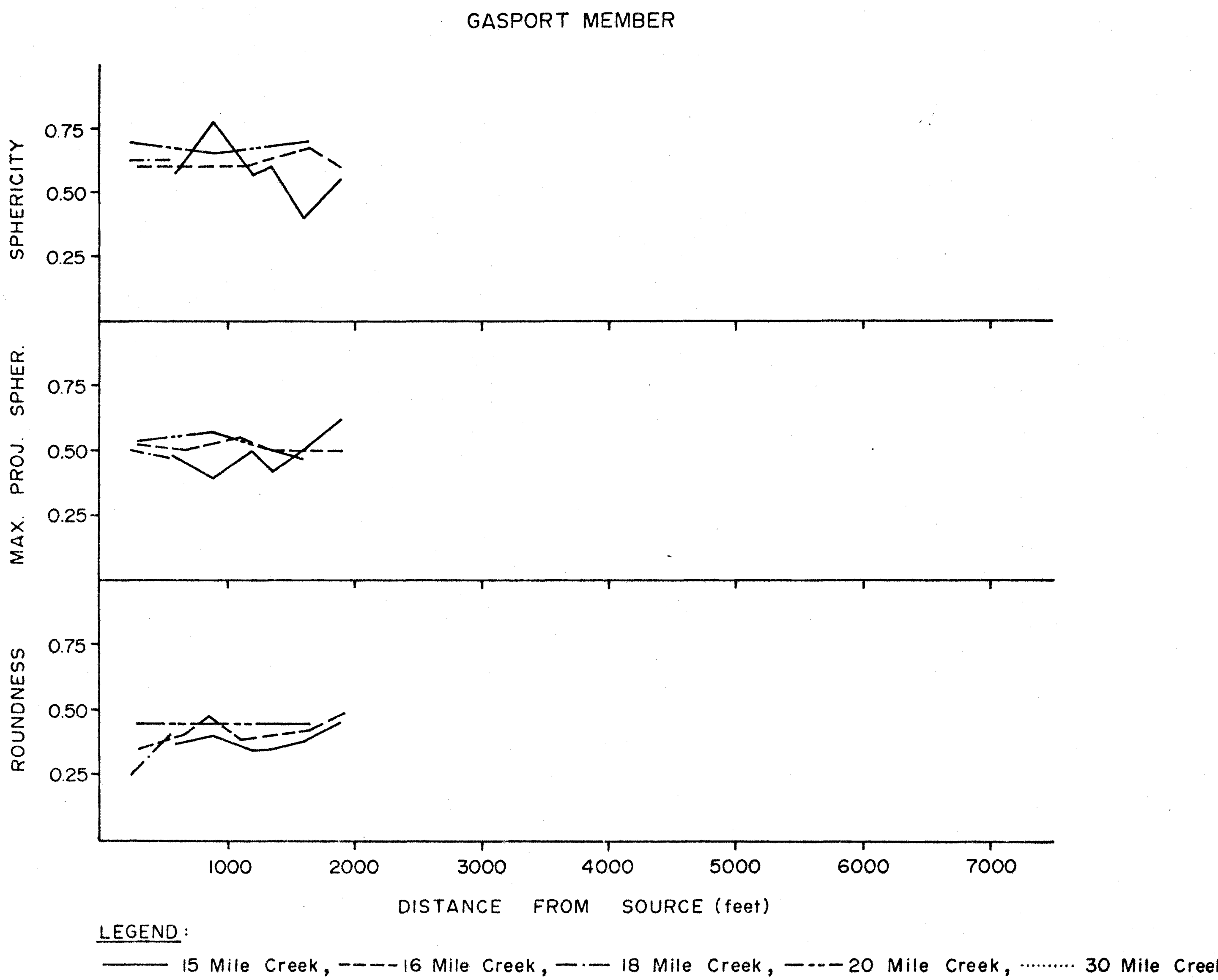

Fig. 26. Downstream changes in sphericity, maximum projection sphericity and roundness - Gasport Member. (1,000 ft. = 305 m).

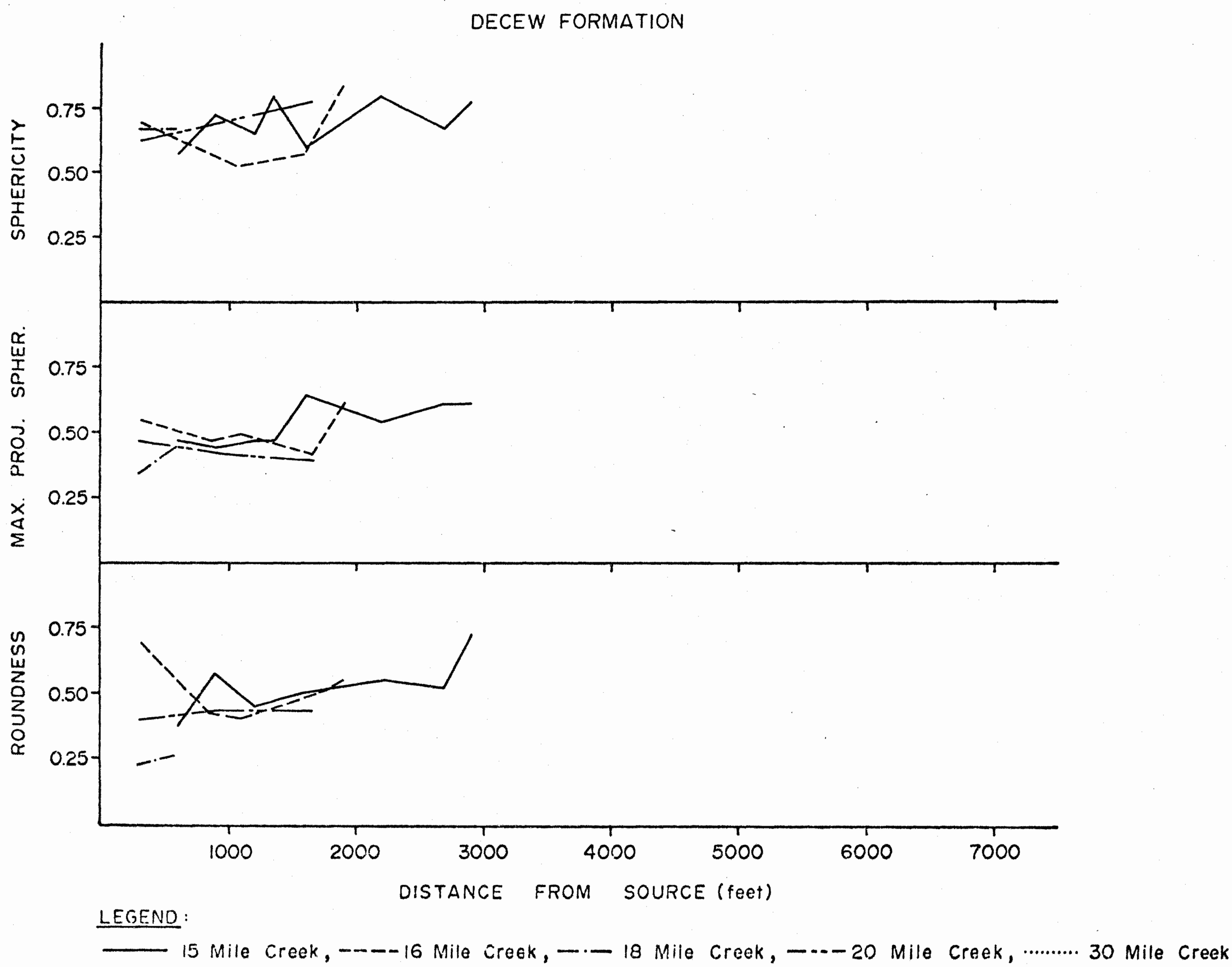

Fig. 27. Downstream changes in sphericity, maximum projection sphericity and roughness - DeCew Formation.

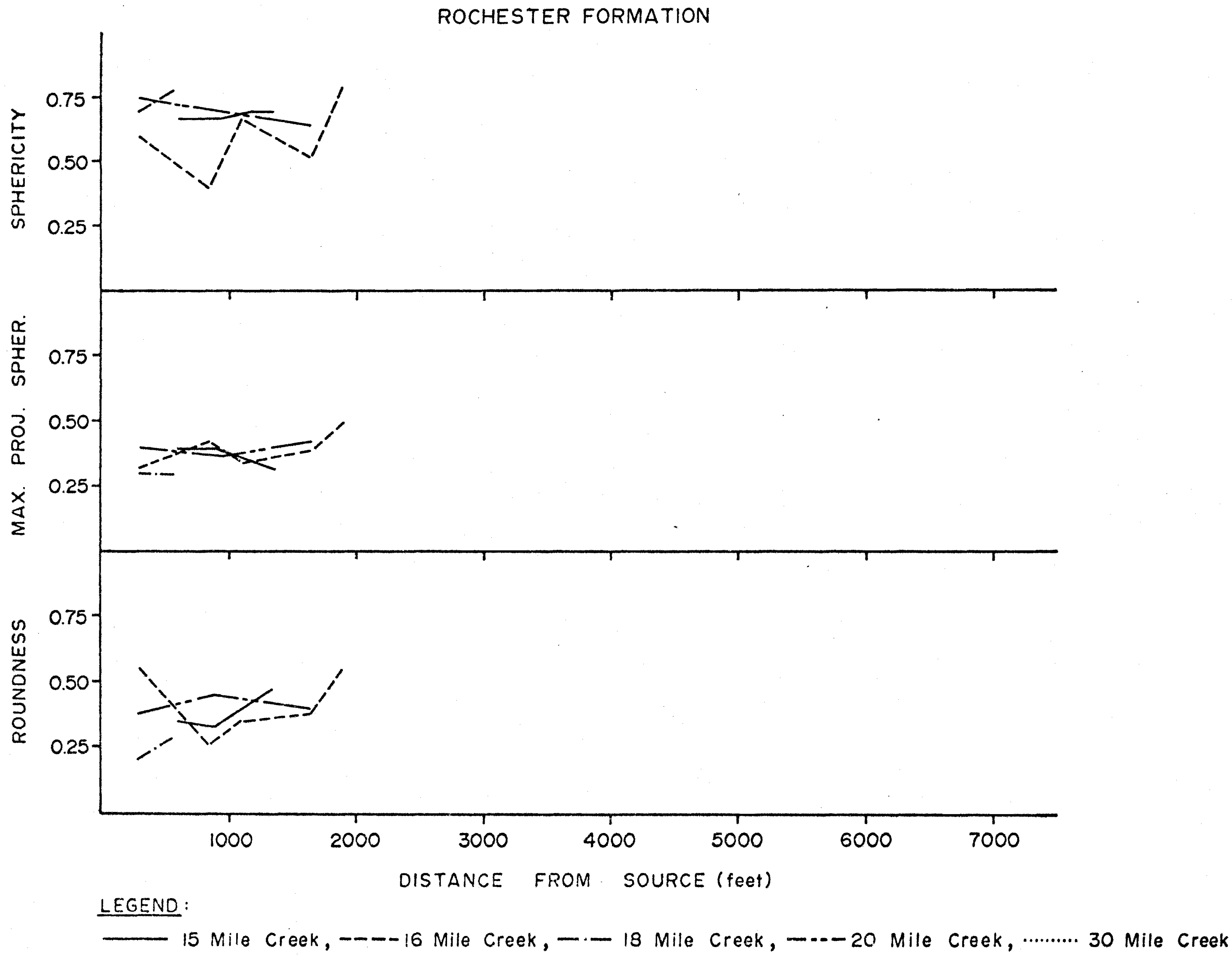

Fig. 28. Downstream changes in sphericity, maximum projection sphericity and roundness - Rochester Formation.

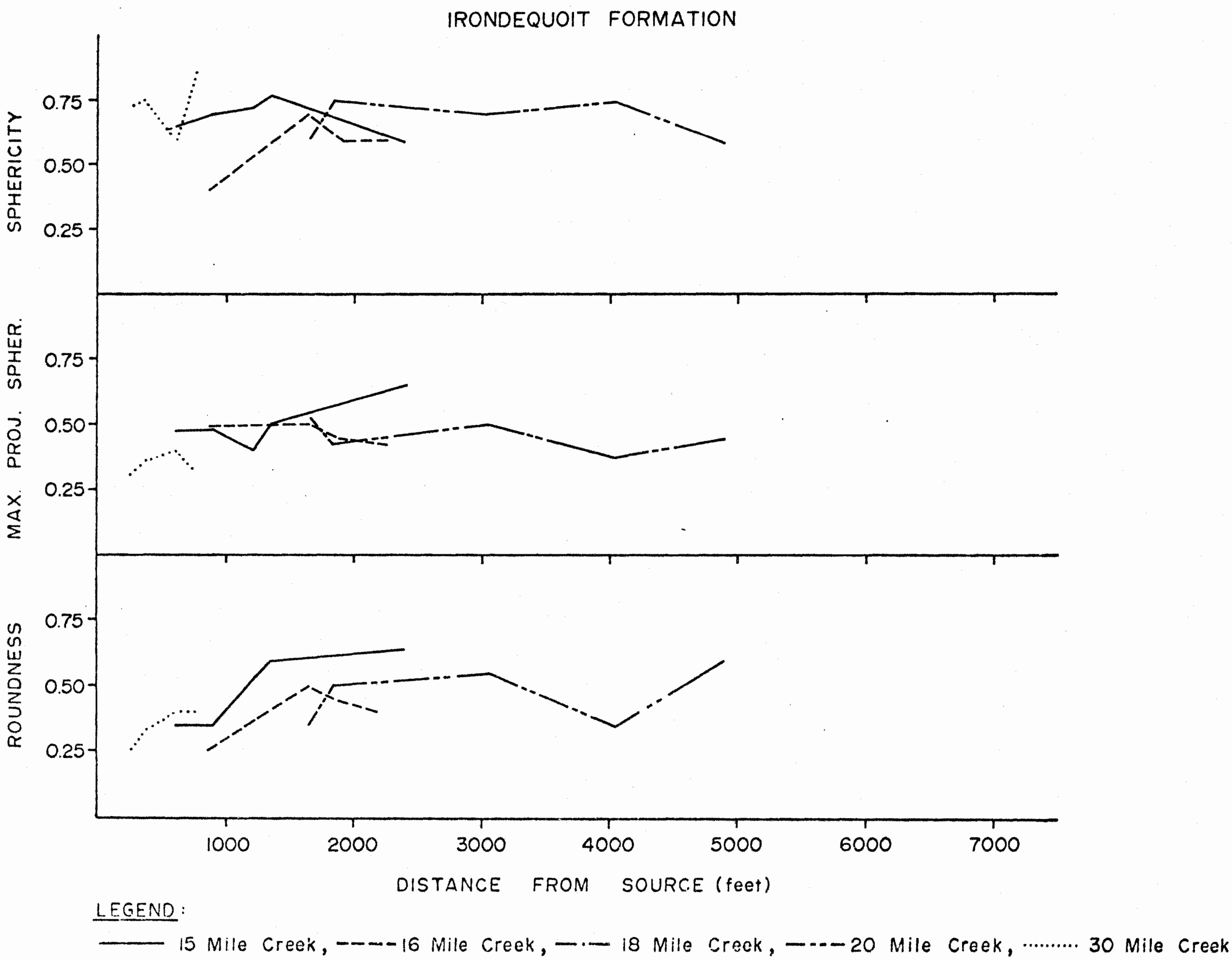

Fig. 29. Downstream changes in sphericity, maximum projection sphericity and roundness - Irondequoit Formation.

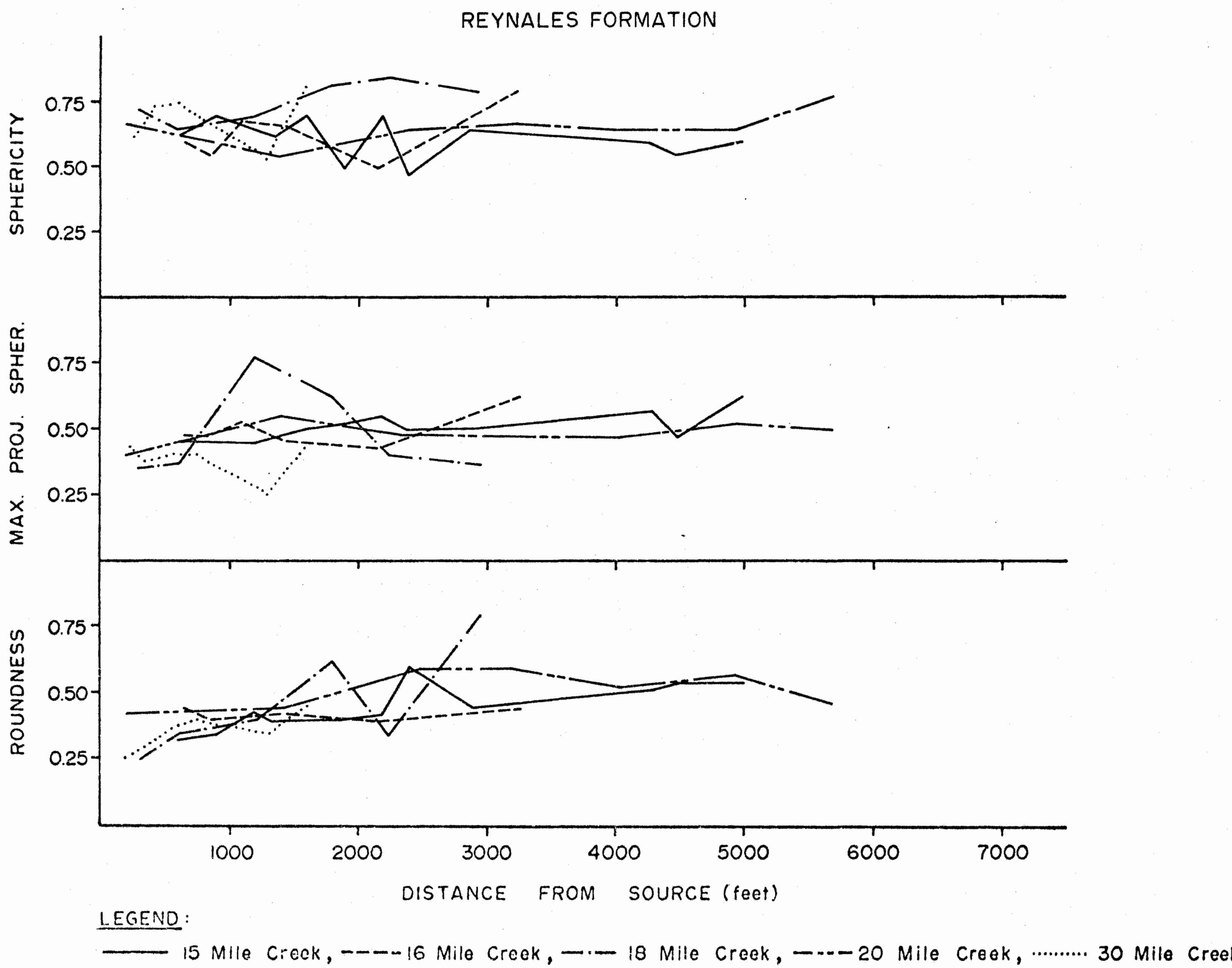

Fig. 30. Downstream changes in sphericity, maximum projection sphericity and roundness - Reynales Formation.

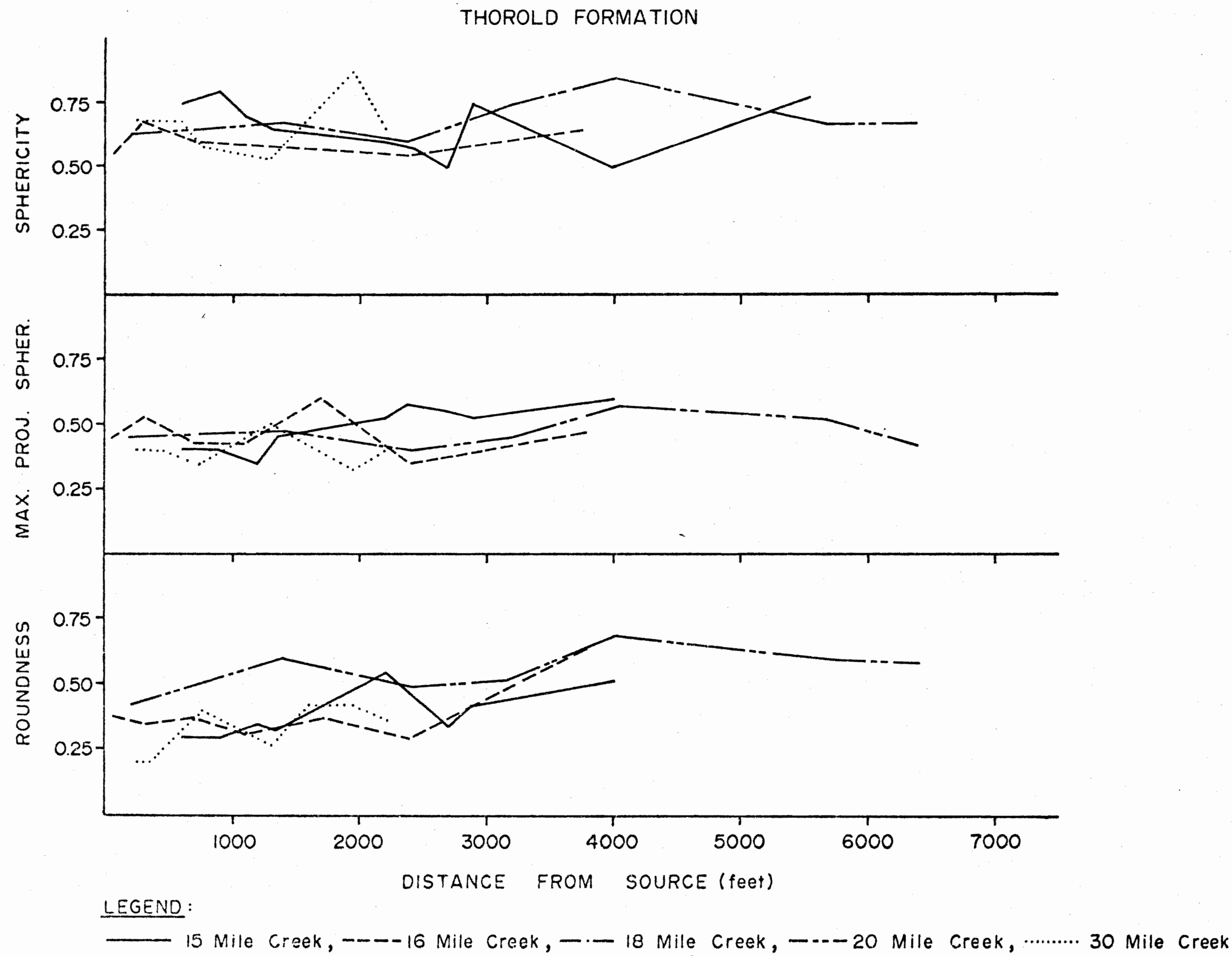

Fig. 31. Downstream changes in sphericity, maximum projection sphericity and roundness - Thorold Formation.

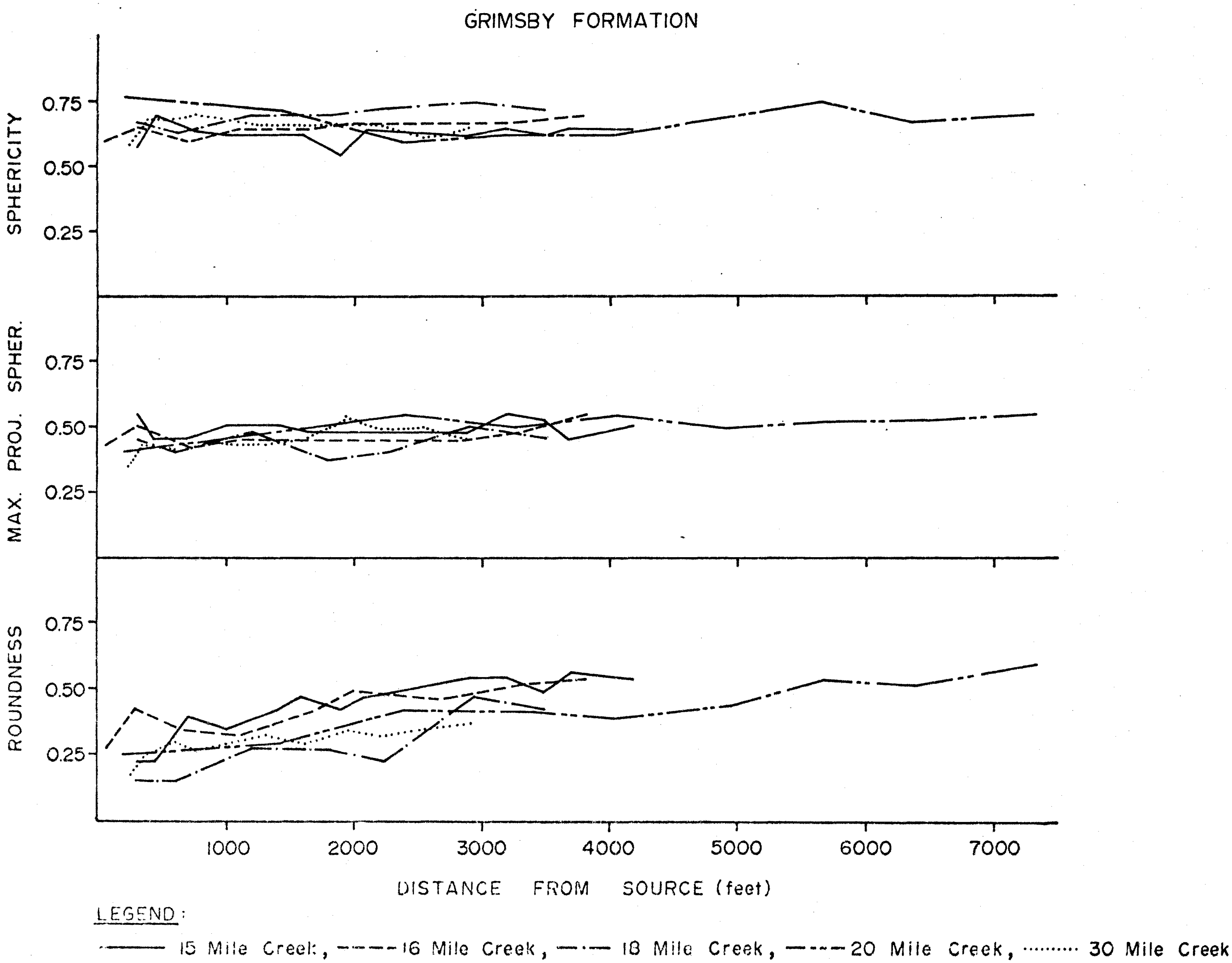

Fig. 32. Downstream changes in sphericity, maximum projection sphericity and roundness - Grimsby Formation.

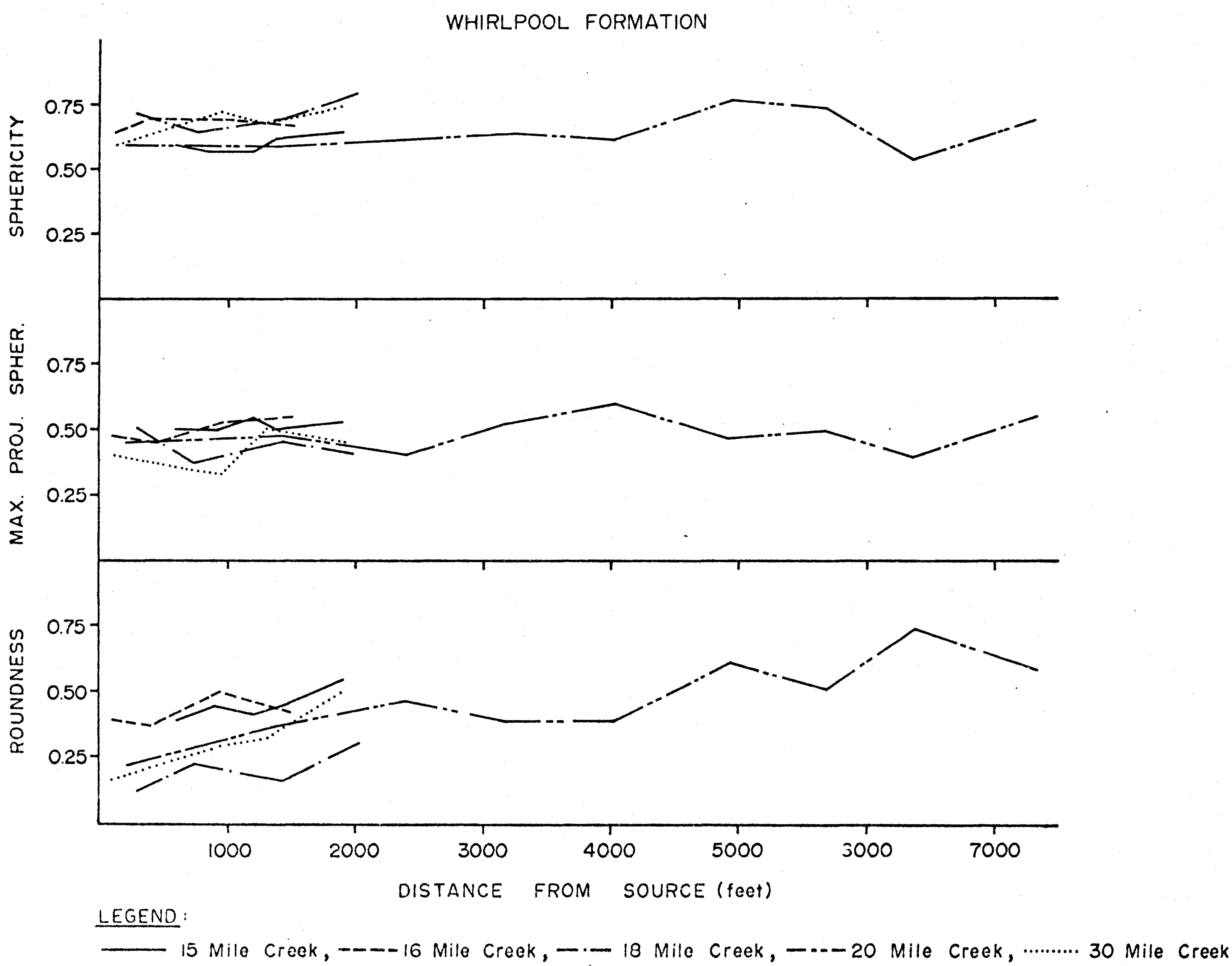

Fig. 33. Downstream changes in sphericity, maximum projection sphericity and roundness - Whirlpool Formation.

TABLE 3. Linear regression and correlation coefficients for the downstream change sphericity, maximum projection, sphericity and roundness (individual lithologies)

Formation	Creek		Sphericity			Maximum Projection Sphericity			Roundness		
		n	a	b	r	a	b	r	a	b	r
Gasport (carb)	15 Mile	6	-0.0001	0.74	-0.50	0.0001	0.34	0.67	-	0.34	0.38
	16 Mile	6	-	0.59	0.43	-	0.53	-0.34	-	0.37	0.59
	20 Mile	3	-	0.68	0.29	-	0.54	-0.29	-	0.44	-0.84
DeCew (carb)	15 Mile	8	0.0001	0.61	0.46	0.0001	0.42	0.76	0.0001	0.37	0.74
	16 Mile	5	0.0002	0.33	0.72	0.0001	0.41	0.44	0.0001	0.29	0.92
	20 Mile	3	0.0001	0.62	0.97	-	0.49	-0.99	-	0.39	0.84
Rochester (sh)	15 Mile	4	-	0.66	0.91	-0.0001	0.49	-0.94	0.0002	0.20	0.88
	16 Mile	5	0.0001	0.48	0.45	0.0001	0.31	0.73	-	0.40	0.05
	20 Mile	3	-0.0001	0.77	0.00	-	0.40	0.99	-	0.40	0.10
Irondequoit (carb)	15 Mile	5	-	0.74	0.39	0.0001	0.37	0.81	0.0002	0.27	0.86
	16 Mile	4	0.0002	0.33	0.67	-	0.51	-0.51	0.0001	0.19	0.68
	20 Mile	5	-	0.70	-0.12	-	0.51	-0.45	-	0.37	0.39
Reynales (carb)	15 Mile	12	-	0.66	-0.37	-	0.44	0.74	-	0.34	0.81
	16 Mile	7	0.0001	0.54	0.54	0.0001	0.41	0.75	-	0.39	0.33
	18 Mile	6	0.0001	0.67	0.78	-	0.48	0.06	0.0002	0.20	0.80
	20 Mile	7	-	0.60	0.57	-	0.45	0.40	-	0.47	0.40
	30 Mile	6	-	0.66	0.06	-	0.40	-0.26	0.0001	0.25	0.88
Thorold	15 Mile	9	-0.0001	0.79	-0.71	0.0001	0.35	0.90	0.0001	0.26	0.76
	16 Mile	7	-	0.61	0.02	-	0.47	-0.02	0.0001	0.31	0.67
	20 Mile	7	-	0.64	0.36	-	0.46	0.14	-	0.48	0.62
	30 Mile	8	-	0.60	0.36	-	0.38	0.20	0.0001	0.22	0.73

TABLE 3 (con't)

Formation	Creek	n	Sphericity a	Sphericity b	Sphericity r	Maximum Projection Sphericity a	Maximum Projection Sphericity b	Maximum Projection Sphericity r	Roundness a	Roundness b	Roundness r
Grimsby (ss)	15 Mile	13	-	0.62	0.08	-	0.49	-0.01	0.0001	0.28	0.91
	16 Mile	9	-	0.62	0.83	-	0.44	0.61	0.0001	0.32	0.87
	18 Mile	7	-	0.65	0.84	-	0.41	0.30	0.0001	0.12	0.89
	20 Mile	9	-	0.69	-0.10	-	0.46	0.61	-	0.26	0.94
	30 Mile	10	-	0.67	-0.24	-	0.39	0.74	0.0001	0.22	0.84
Whirlpool (ss)	15 Mile	5	-0.0001	0.54	0.73	-	0.50	0.25	0.0001	0.34	0.87
	16 Mile	4	-	0.66	0.55	0.0001	0.46	0.92	-	0.39	0.57
	18 Mile	4	-	0.67	0.55	-	0.47	-0.41	0.0001	0.12	0.81
	20 Mile	9	-	0.61	0.39	-	0.47	0.22	0.0001	0.26	0.87
	30 Mile	4	0.0001	0.60	0.85	-	0.38	0.42	0.0002	0.15	0.97

NOTE:
carb: carbonate sediments
sh: shale sediments
ss: sandstone sediments
n: number of sample points
a: slope
b: y-intercept
r: correlation coefficients
(absent values indicate no slope)

is 0.60 and increases to 0.70 over distances of 2,000 to 3,000 feet (610 to 915 m) at the final sampling stations. Although the Reynales fragments on 15 Mile and 20 Mile Creeks have been transported distances beyond this range, up to 5,000 feet (1525 m), the average initial and final values, of 0.63 and 0.69, respectively, are similar to those on the other streams. Slope values from the regressions suggest that some of the carbonate fragments have a very slight downstream increase in sphericity. However, nearly 80 per cent of the correlation coefficients are less than 0.70 indicating that there is a poor relation between sphericity and distance. Thus downstream variations in sphericity are influenced by the same factors which cause changes in the axial lengths, such as log jams and outcrop benches.

The data in Table 3 also indicate that coarse-grained, fossiliferous fragments of the Gasport and Irondequoit units have larger downstream variations in sphericity than the fine-grained, crystalline sediments of the DeCew and Reynales Formations. This variability likely results from the porous, fossiliferous nature of the coarse-grained lithologies which yield a large range of spall sizes during transport. In contrast, it appears that fine-grained, crystalline lithologies tend to produce less variable spall sizes during transport because of their greater internal strength.

The average initial sphericity of the sandstone pebbles

(Thorold, Grimsby, Whirlpool) is 0.64 and increases to 0.70 at the last sampling stations over distances of 4,000 to 7,000 feet (1220 to 2135 m). Sandstone fragments have a slightly greater initial sphericity than carbonate sediments. Slope values for the sandstone sediments are very low and suggest a negligible downstream increase in sphericity. Seventy per cent of the correlation coefficients are less than 0.70, indicating that sandstone sphericity is slightly more dependent on transport distance than carbonate, however, there is still a poor correlation.

Results of this study compare favourably with those of other workers. Krumbein (1940), Hadley (1960), and Scott and Gravlee (1968), determined that downstream changes in sphericity were nonsystematic and appeared to be independent of transport distance. In the present study, it was also shown that downstream sphericity changes were nonsystematic and because sphericity is directly related to axial lengths, it seems that the factors which cause variations in axial lengths, such as log jams and outcrop benches, also cause changes in visual sphericity.

Maximum projection sphericity is the least variable textural characteristic of both carbonate and sandstone fragments and was used in this study as an objective measure of sediment sphericity. The range of intercept values for carbonate and sandstone fragments is relatively small and their average value is 0.52. The negligible slope values for both lithologic groups suggest that there is no downstream increase in the maximum projection sphericity, thus, the average value at the final downstream sampling station is also 0.52. Examination of the figures and correlation coefficients indicate that the values for the carbonates are slightly more variable than sandstones.

Because these values are calculated from the lengths of the axes, the slightly greater variability in the axial lengths of the carbonate pebbles causes a greater downstream variation in their maximum projection sphericity. Correlation coefficients between maximum projection sphericity and distance have a wide range, both positive and negative, suggesting that there is no definite trend between these two variables.

Previous studies of downstream changes in maximum projection sphericity by Sneed and Folk (1958) have shown that for particles greater than 60 mm, the values remain nearly constant downstream over a distance of 270 miles (432 km). Although the sediments examined in this study were sampled over distances of up to two miles (3.2 km) and were coarser 10 to 15 cm in diameter, than those analysed by Sneed and Folk (1958), it was also found that the maximum projection sphericity did not change with increasing transport distance.

The average initial roundness of the carbonate fragments, based on the intercept, is 0.33. At the termination of the study reaches, which occur between 2,000 and 3,000 feet

(610 and 915 m) downstream of the initial samples, pebble roundness increases to 0.55. According to the classification of Pettijohn (1975, p.57), this increase indicates that the fragments change from subrounded to rounded. The slope values from the regressions show that carbonate pebble roundness increases at a very slow rate. Examination of the figures also suggest that the roundness of some lithologies may increase more rapdily over the first half of their transport distances than in the downstream sections, however, this is not a prevalent characteristic of all carbonate lithologies. Fifty-four per cent of the correlation coefficients are greater than 0.70, implying that there is a good relation between roundness and distance for at least half of the lithologies examined.

The average intercept value for sandstone pebbles is 0.26, indicating that sandstone fragments are initially more angular than carbonates. At the final downstream samples, which occur between 4,000 and 7,000 feet (1220 and 2135 m) downstream of the initial samples, the average value increases to 0.57, thus sandstone pebbles also change from subrounded to rounded. Nearly 80 per cent of the correlation coefficients are greater than 0.70 which implies that sandstone pebble roundness is better correlated with distance than carbonate pebbles. The greater variability of the Thorold clasts, compared with the Grimsby or Whirlpool, results from their low sample percentages, less than 10 per cent, which accounts for larger variations in roundness values.

Studies of pebble roundness by Krumbein (1940), Sneed and Folk (1958), Hadley (1960), and Scott and Gravlee (1968) have shown that roundness variations are related to sediment lithology. The data obtained for this study also show that the increase in sandstone roundness was greater than the increase in carbonates and that sandstone pebble roundness is better correlated with distance than carbonates. Their results also demonstrated that pebble roundness increases more rapidly in the upper sections of the rivers studied than farther downstream. However, the present data suggests that only some of the lithologies exhibit this trend, and that this is not a common characteristic of all lithologies.

HYDROLOGY AND SEDIMENT TRANSPORT

Fluorometric Velocity Measurements

Fluorometric velocity measurements were made over two reaches of 20 Mile Creek during November and December, 1976. Both reaches are located downstream of the gauging station at Balls Falls. The upper reach is near the Highway 8 bridge and the lower section is in the vicinity of the Jordan Valley Campground, near the lower bridge (fig. 1). These reaches were chosen because they are easily accessible and because they represent the normal channel conditions of the study area.

The Highway 8 reach is 354 feet (108 m) long with an average gradient of 0.0045 and extends through two riffles and one pool. During the latter part of December, ice conditions prevailed which partially blocked the flow and diverted some of the water beyond the monitoring cross-section. The lower reach is 231 feet (70.5 m) in length with an average gradient of 0.0038 and has one small riffle and one large pool. Near the end of this reach, the flow diverted across a bar and therefore, total discharge could not be measured. At both sections, the channel width at the observation point is 10 feet (3.0 m) with an average depth of one foot (0.30 m). Nine fluorometric runs were made at the upper site and ten runs were made at the lower section. Following the completion of a run, the discharge and average velocity were measured with a current meter at the same cross-section for each site.

Figures 34 and 35 illustrate the change in dye concentration with time. The time-concentration curves are negatively skewed as a result of the dispersion which occurs over the travel distance. Thackston and Krenkel (1967) have determined that longitudinal dye dispersion results from variations in the flow velocity across the channel cross-section and that dispersion is also affected by turbulent diffusion of the dye into the slower moving flow near the channel boundaries. Day (1978, p.451) has also suggested that, "the distinct downstream asymmetry of the curves is most likely caused by the trapping and subsequent slow release of tagged particles from dead or slowly moving zones along the flow boundary". Because of these variations in flow velocities, there is a lag between the arrival times of the initial and modal concentrations. With increasing stream velocity, the lag time is reduced and the rising and falling limbs of the curves become steeper, suggesting that dispersion is inversely proportional to velocity and discharge.

Tables 4 and 5 show the velocity and discharge data derived from fluorometric and current meter measurements. The first appearance of the dye was used to calculate the initial velocity (Vi) which represents the fastest portion of the flow. The arrival time of the maximum concentration was used to determine the modal velocity (Vm) for the reach. The current meter velocity (Vc) is an average across a channel cross-section and therefore, represents only one point measurement which is very much dependent on the particular section.

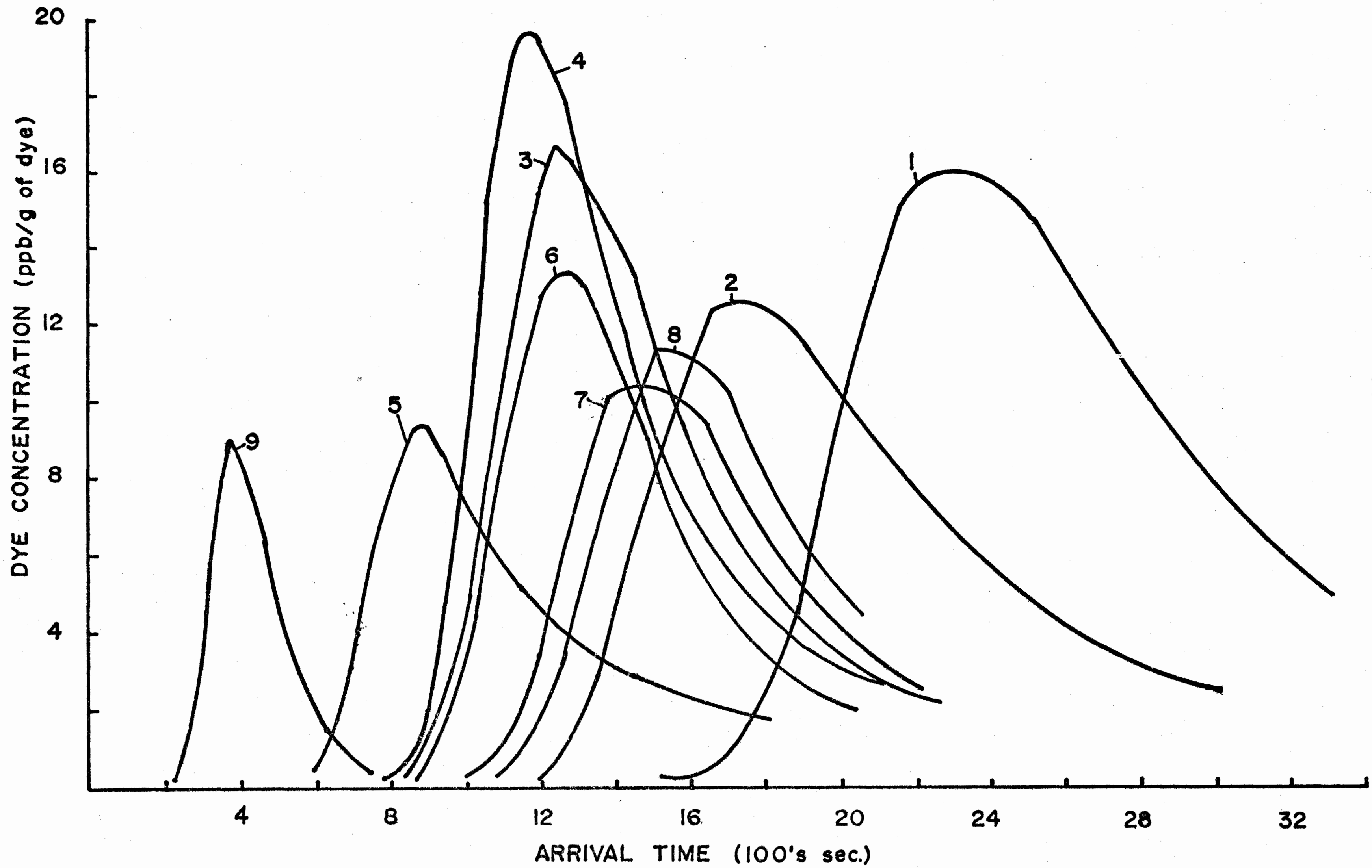

Fig. 34. Time - concentration curves for fluorometric runs - Highway 8 Bridge.
(Curve numbers correspond to numbered data in Table 4.)

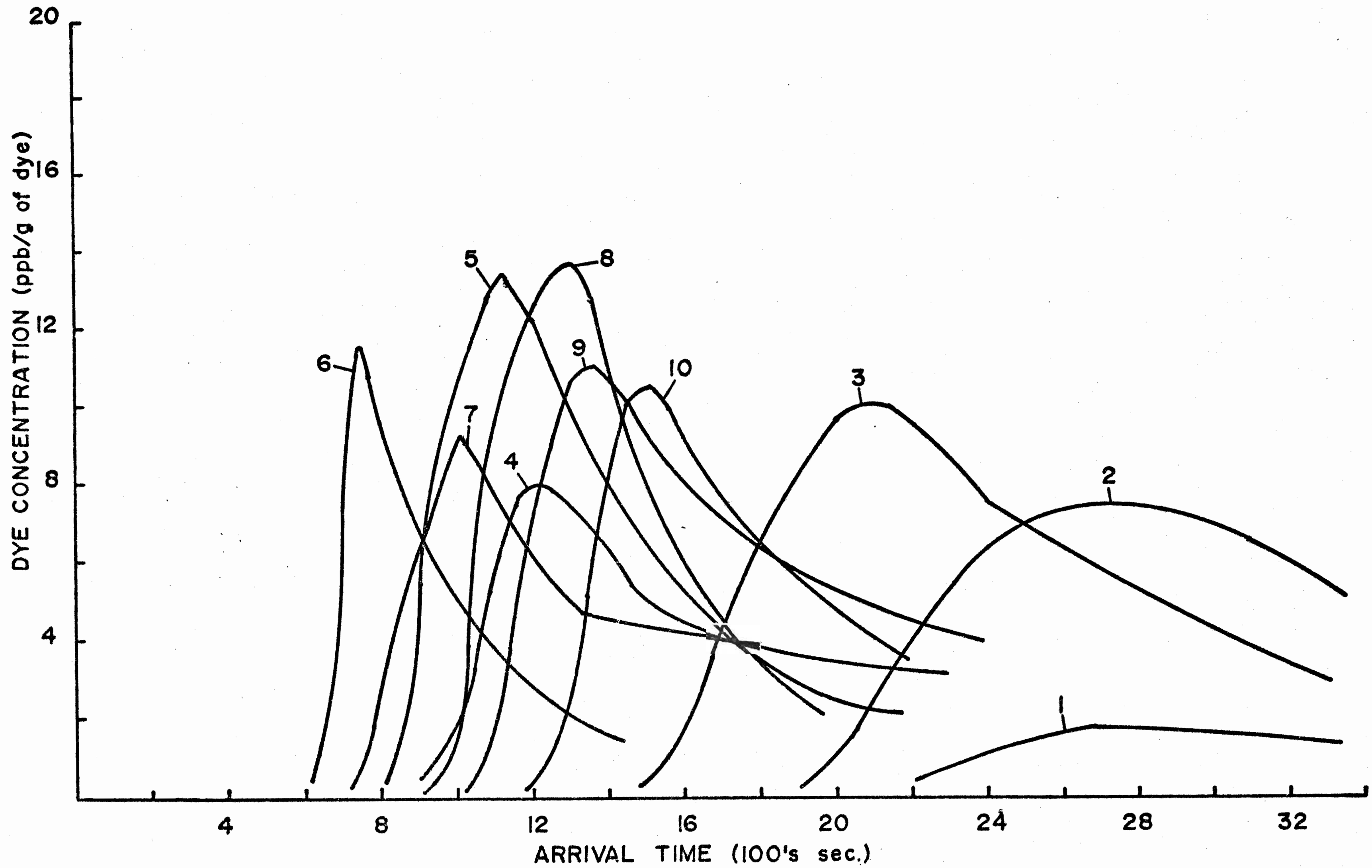

Fig. 35. Time - concentration curves for fluorometric runs - Lower Bridge. (Curve numbers correspond to numbered data in Table 5.)

TABLE 4. Velocity and dishcarge measurements - Highway 8 Bridge.

	Arrival Times (sec.)		Fluorometer Velocity Measurements (ft./sec.)		Current Meter Velocity Measurements (Vc) (ft./sec.)	Measured Discharge (cfs)
	Initial	Peak	Initial (Vi)	Modal (Vm)		
1 -	1560	2280	0.23	0.16	0.33	1.47
2 -	1200	1760	0.30	0.29	0.34	2.08
3 -	840	1240	0.42	0.29	0.44	2.22
4 -	780	1160	0.45	0.31	0.37	2.10
5 -	540	880	0.66	0.40	0.62	14.5
6 -	800	1220	0.44	0.29	0.55	3.19
7 -	960	1440	0.37	0.25	0.45	2.23
8 -	1080	1520	0.33	0.23	0.40	2.07
9 -	220	380	1.61	0.93	0.84	23.47

distance = 354 feet (108 m)
drop = 1.61 feet (0.49 m)
gradient = 0.0045
(1 ft./sec. = 30.5 cm/s; 1 cfs = 0.028 m^3/s)

TABLE 5. Velocity and discharge measurements - Lower Bridge.

	Arrival Times (sec.)		Fluorometer Velocity Measurements (ft./sec.)		Current Meter Velocity Measurements (Vc) (ft./sec.)	Measured Discharge (cfs)
	Initial	Peak	Initial (Vi)	Modal (Vm)		
1 -	2100	2680	0.11	0.09	0.19	0.81
2 -	1860	2680	0.12	0.09	0.31	1.14
3 -	1460	2100	0.16	0.11	0.37	1.04
4 -	900	1200	0.26	0.19	0.57	2.63
5 -	780	1120	0.30	0.21	0.65	2.55
6 -	600	740	0.39	0.31	0.82	3.85
7 -	730	1000	0.32	0.23	0.64	2.48
8 -	900	1280	0.26	0.18	0.57	2.38
9 -	1020	1340	0.23	0.17	0.53	2.15
10 -	1170	1500	0.20	0.15	0.51	1.81

distance = 231 feet (70.5 m)
drop = 0.88 feet (0.27 m)
gradient = 0.0038
(1 ft./sec. = 30.5 cm/s; 1 cfs = 0.028 m^3/s)

Figures 36 and 37 illustrate the relations between the fluorometric and current meter velocities for the Highway 8 and lower bridge sites, respectively. At both reaches the modal velocity is less than the current meter velocity because the channel is narrower at the observation points than over the lengths of the reaches. The diagrams also indicate that the curves for the lower reach are not as steep as those for the upper reach. At the Highway 8 reach, the pool downstream of the first riffle is short and narrow, whereas at the lower bridge, the pool downstream of the first riffle is about twice the length and breadth of the pool at the upper site. Consequently, at a given discharge, the flow at the upper site has a greater velocity due to differences in channel geometry.

The relations between discharge and the current meter (Vc) and modal velocities (Vm) are shown in figures 38 and 39. Linear regressions were derived for both reaches using the hydraulic geometry equations proposed by Leopold and Maddock (1953). The equations for the upper reach are

$$Vc = 0.32\ Q^{0.29} \quad r = 0.92 \quad (1)$$

$$Vm = 0.18\ Q^{0.44} \quad r = 0.89 \quad (2)$$

and for the lower reach,

$$Vc = 0.28\ Q^{0.83} \quad r = 0.96 \quad (3)$$

$$Vm = 0.10\ Q^{0.80} \quad r = 0.97 \quad (4).$$

All of the equations show good correlations and exponents for the upper site are similar to those presented by Leopold, Wolman and Miller (1964, p.244, Table 7-5). The

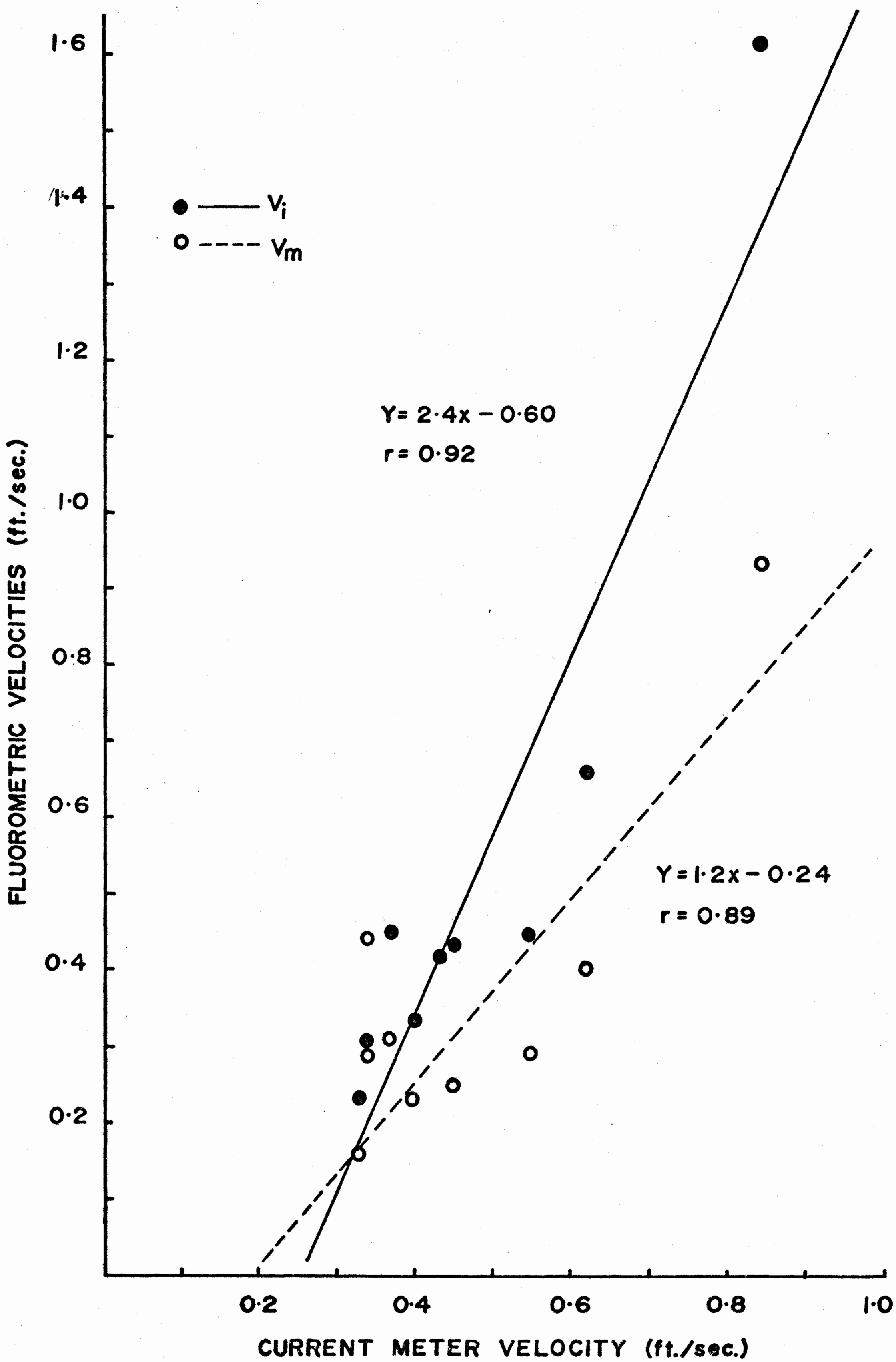

Fig. 36. Fluorometric and current meter velocity relations - Highway 8 Bridge. (1 ft./sec.= 30.5 cm/s).

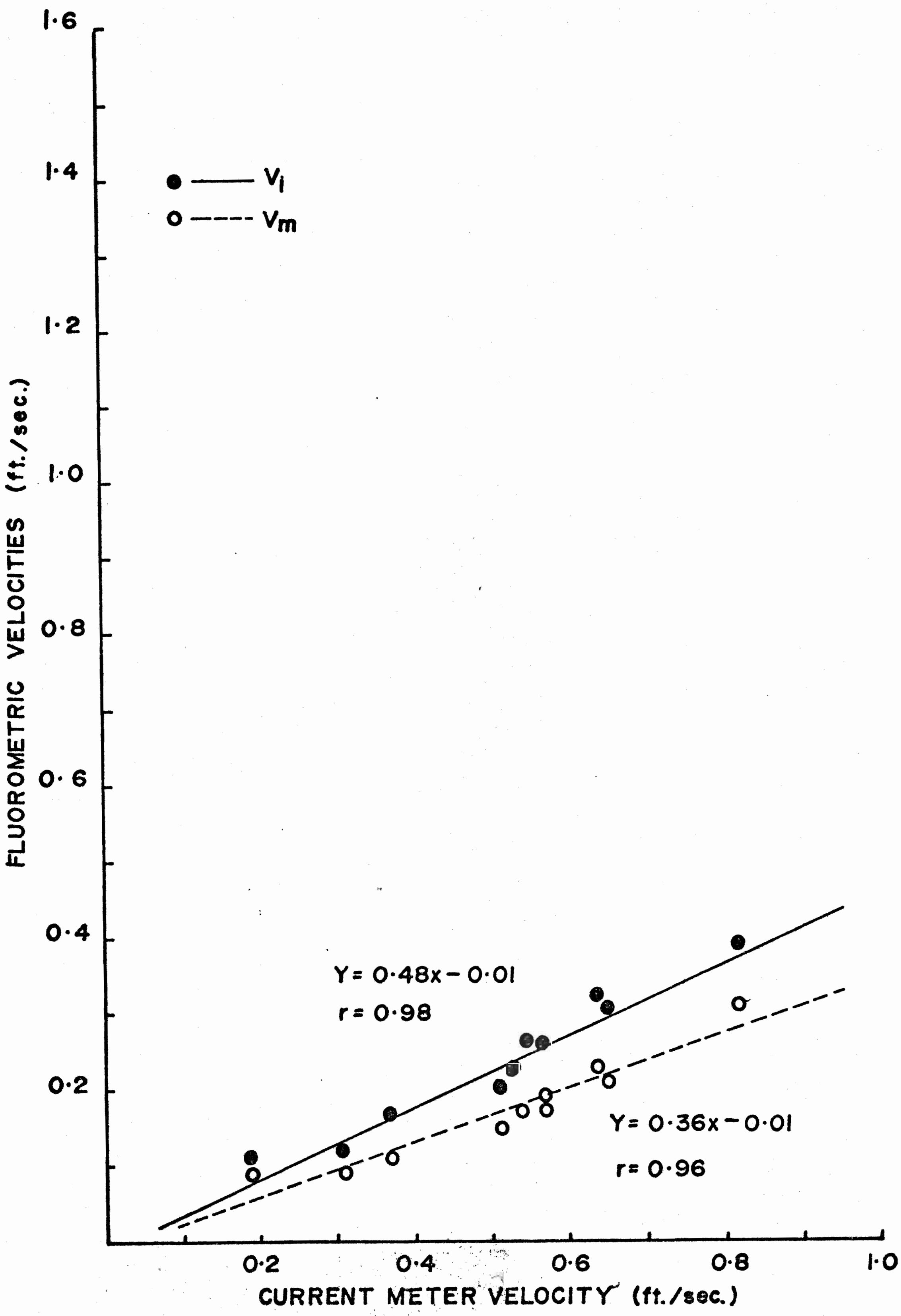

Fig. 37. Fluorometric and current meter velocity relations - Lower Bridge. (1 ft./sec. = 30.5 cm/s).

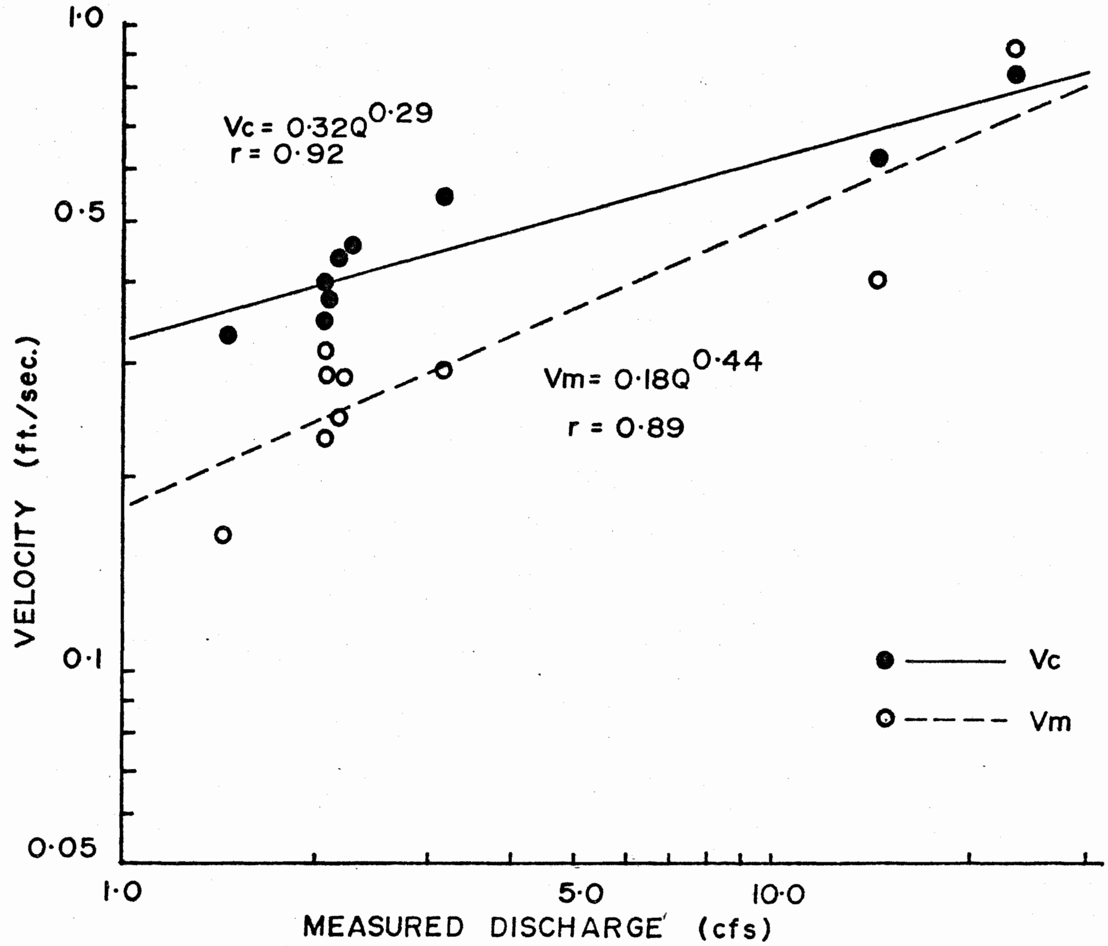

Fig. 38. Velocity-discharge relations - Highway 8 Bridge. (1 cfs = 0.028 m3/s).

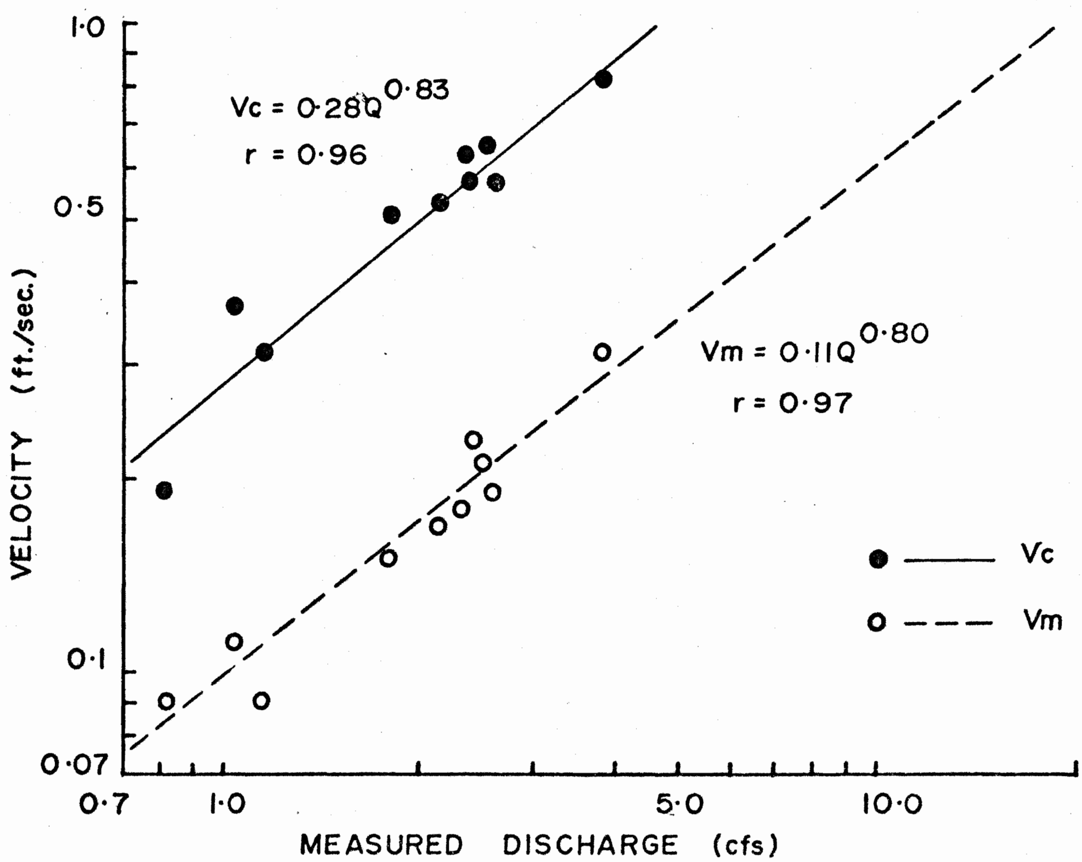

Fig. 39. Velocity-discharge relations - Lower Bridge. (1 cfs = 0.028 m3/s).

exponents for the lower reach, however, are much greater indicating that velocity increases rapidly with discharge. The average discharge (6.0 cfs) measured at the upper reach is about three times greater than the average (2.1 cfs) at the lower site. Wilcock (1971) determined that low flows result in artificially high rates of velocity increase with discharge. In addition, the sediments in the Highway 8 reach are considerably coarser than those at the lower reach, consequently it is possible that flow resistance decreases downstream causing a more rapid increase in velocity, as previously reported by Leopold, Wolman and Miller (1964) and Wilcock (1971).

Frequency of Sediment Movement

Sediments resting on a stream bed will not begin to move until the flow attains a certain intensity required to initiate transport. There are two mechanisms which cause sediment movement: the fluid drag which rolls the particles along the bed and the hydrodynamic lift force which lifts grains from the bed and projects them into the faster moving flow (Blatt, Middleton and Murray, 1972). Because these forces are directly related to velocity, the initiation of particle movement is commonly determined form the relation between velocity and intermediate particle diameter. The Hjulstrom (1935) and Shields (1936) diagrams are often used in relating these two parameters, although both have their limitations. The Hjulstrom diagram relates the critical velocity for sediment movement with flows at least 1.0 m deep and the Shield diagram applies "only to the movement of grains on an originally flat bed composed of well-sorted grains" (Blatt, Middleton and Murray, 1972, p.92).

The average intermediate diameter of the pebbles in the study reaches is 10 cm. The Hjulstrom diagram (fig. 40) indicates that the critical velocities required to initiate motion range from 200 cm/sec to 300 cm/sec (6.6 ft./sec. to 9.8 ft./sec.). From equations (1) to (4), the discharges corresponding to these velocities have a considerable range. The values obtained from the equations (1) and (3) relating current meter velocity to discharge range from less than 100 cfs (3.0 m^3/s) to greater than 30,000 cfs (850 m^3/s). Because this range is unrealistic and flows of 30,000 cfs (850 m^3/s) have never been recorded on 20 Mile Creek, these discharge values may be rejected. Discharges calculated from the modal velocity equations (2) and (4) range from 3,500 cfs to 7,500 cfs (99 m^3/s to 212 m^3/s) at the upper site and 200 cfs to 300 cfs (5.7 m^3/s to 8.5 m^3/s) at the lower reach. The small range of flows for the lower bridge site is a result of the previously mentioned factors affecting the velocity-discharge relations.

A flow duration curve was constructed for 20 Mile Creek using the procedure outlined by Searcy (1959) and is shown in figure 41. Discharges were divided into 25 to 30 class intervals and the frequency of each event was tallied to calculate the cumulative percentages. Mean daily discharges for the last five years were used to construct this curve.

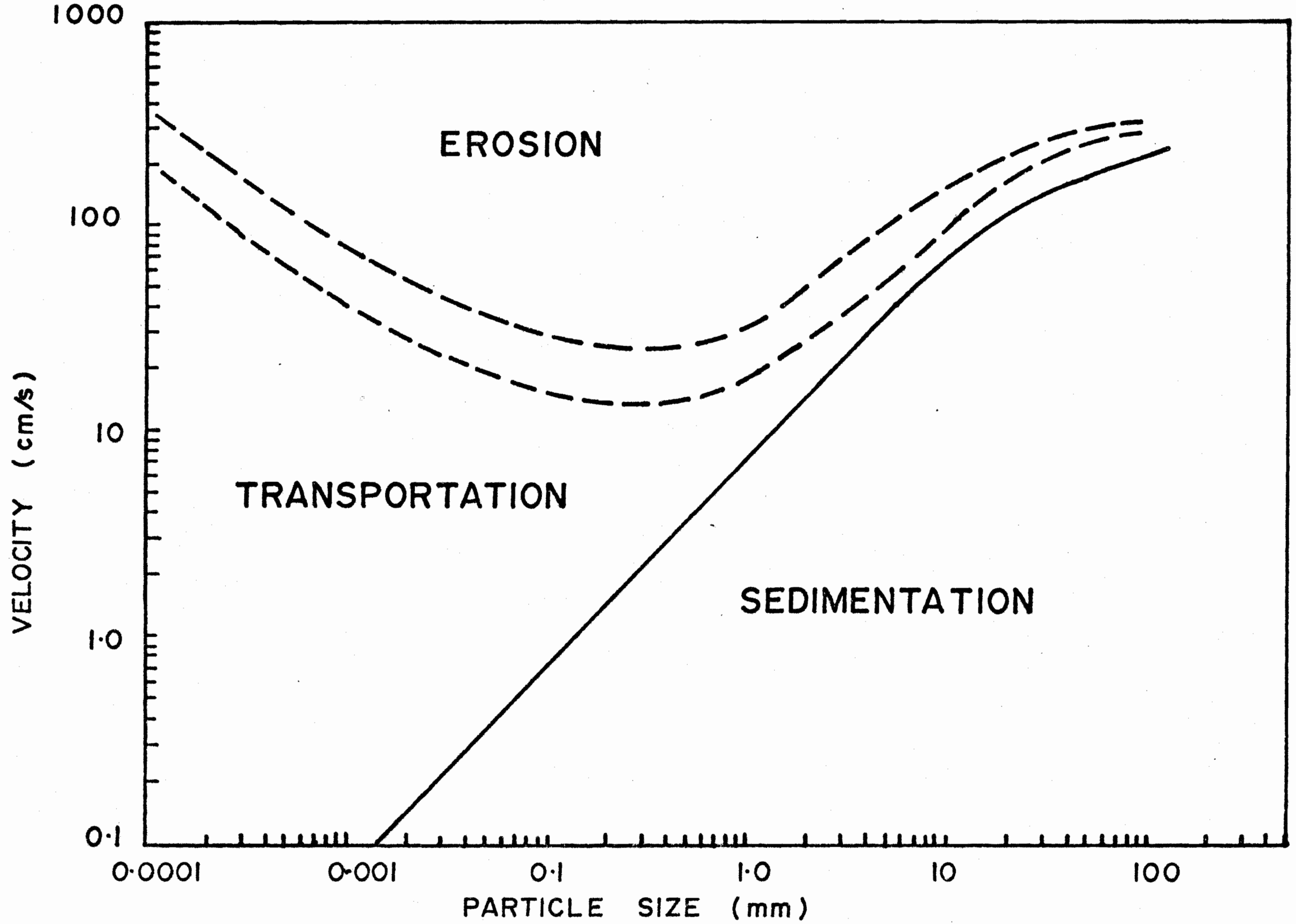

Fig. 40. Hjulstrom Diagram (after Hjulstrom, 1935).

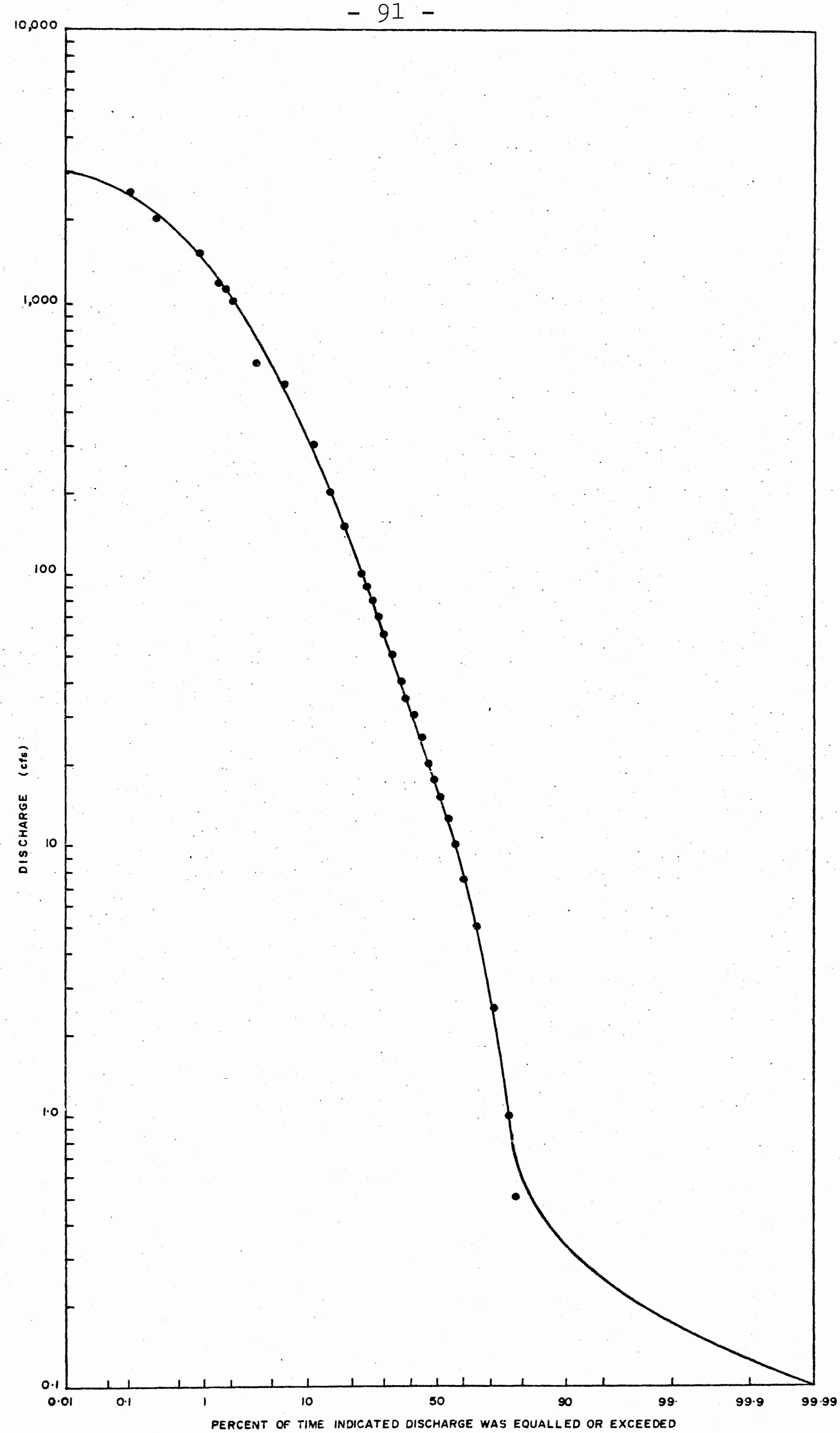

Fig. 41. Flow duration curve for 20 Mile Creek.

The flow duration curve indicates that 50 per cent of the time, the discharge on 20 Mile Creek is less than 20 cfs (0.57 m^3/s) and that flows equal to or greater than 300 cfs (8.5 m^3/s) occur less than 10 per cent of the time. Mean daily flow records published by the Water Survey of Canada show that discharges of the spring flood are generally greater than 500 cfs (14 m^3/s) and most are over 1,000 cfs (28 m^3/s).

The range of discharges derived from equation (2) occur less than 0.01 per cent of the time. Because these relations are based on extremely low flow conditions, the majority of the measured discharges are less than 5 cfs (0.14 m^3/s), the water depth is generally less than one foot (0.30 m). As a result, the coarse sediments in the channels cause an increase in flow resistance which reduces the velocity, as previously suggested by Wilcock (1971). Furthermore, as previously mentioned, total discharge at both reaches could not be measured, consequently the modal velocity actually corresponds to greater flows than the measured discharges. Thus, it is probable that the calculated discharges are too low for their corresponding fluorometric velocities and therefore, the sediments are in transport more frequently than suggested.

CONCLUSIONS

Downstream variations in the frequency of individual pebble lithologies are influenced by the outcrop position of the formations in the channels. The dominance of a given lithology within a sample is a function of the thickness and physical characteristics of the source unit, as well as the prevalance of lithologies originating from stratigraphically associated formations. Sediments derived from a single formation generally reach a maximum frequency within the first 1,000 feet (305 m) of transport. Pebbles originating at the brink of waterfalls, reach a maximum frequency farther downstream than sediments derived from the units at the base of waterfalls. Consequently, by-passing of sediment lithologies occurs.

The decrease in sediment size downstream is not systematic as a result of changes in sediment composition and channel morphology. Samples composed of several lithologies are generally coarser than those with a maximum concentration of a given lithology. Axial lengths increase downstream of outcrops because of the influx of material from a new source. In addition, coarse clasts occur upstream of log jams because these obstructions restrict their downstream transport.

Standard deviations of the axial lengths were used to measure sediment sorting. The values generally decrease downstream and reflect variations similar to the changes in axial lengths. Poorly sorted sediments occur upstream of log jams, downstream of outcrop benches and in samples containing a number of lithologies. Well-sorted material is generally found downstream of log jams and in samples with only one or two lithologies.

Linear regression analyses of the downstream changes in the axial lengths of individual pebble lithologies indicate that the long axis decreases in length more rapidly than the intermediate, while the short axial lengths remain nearly constant. Carbonate and sandstone sediments decrease in length at about the same rate. Downstream changes in the axial lengths of coarse-grained, fossiliferous pebbles are more variable than changes in fine-grained carbonates and sandstones.

Average sphericity values for all lithologies combined increase from 0.65 to 0.67 over the lengths of the study reaches and are more variable than maximum projection sphericity or roundness. The low correlation between sphericity and distance suggests that sphericity is independent of transport distance, as previously reported by Sneed and Folk (1958) and Scott and Gravlee (1968).

The maximum projection sphericity has an average value of 0.52 for all lithologies combined and does not increase with distance. This is primarily a result of the consistent length of the short axis and lack of change in the intermediate/long axial ratio. Because this value is an objective representation of sphericity, whereas visual sphericity is a subjective measurement, it may be inferred that the lack of change in the visual sphericity estimates are also valid.

Pebble roundness of carbonate and sandstone sediments changes from subrounded to rounded downstream. The roundness of sandstone pebbles increases at a faster rate than carbonates because the sandstones are initially more angular. With increasing distance, the roundness of both lithologies become less variable.

Peak, or modal velocity of the dye concentration, obtained for two reaches on 20 Mile Creek, was used to define velocity through the reaches. The relations between fluorometric velocities indicate that there is a good correlation between the modal velocity and measured discharge. The Hjulstrom diagram indicates that the velocities required to transport sediments with an average intermediate diameter of 10 cm range from 200 cm/s to 300 cm/s (6.6 ft./sec. to 9.8 ft./sec.). From the modal velocity-discharge equations, the flows corresponding to these velocities are greater than 3.500 cfs (99 m^3/s). These discharges occur less than 0.01 per cent (0.4 days) of the time and represent a flow occurring during the spring flood.

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